SCORE Project

Structural Capacities for Tackling Wicked Problems

2021-1-MK01-KA220-HED-000030188

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Result ID: 5
Result Title: Score Experimentation Report

Co-funded by the European Union

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In this document, we present five reports resulting from the activities conducted in Result No. 5. These include an integrated report and individual reports by each partner for their respective country.

Coordinator:
Ss. Cyril and Methodius University in Skopje, Republic of North Macedonia
Partners:
Sofia University St. Kliment Ohridski, Bulgaria
Czech University of Life Sciences Prague, Czech Republic
Panepistimio Ioanninon, Greece

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INTEGRATED EXPERIMENTATION REPORT

Mapping Commonalities and Differences of Air Pollution on Wicked Problem Matrix for Greece, Czech Republic, Bulgaria and North Macedonia

1. Introduction

This integrated report provides a comparative analysis of four separate reports examining air pollution in Bulgaria, the Czech Republic, Greece, and North Macedonia. The report analyzes these countries through the lens of the Wicked Problem Matrix, focusing on four key dimensions: Complexity, Uncertainty, Conflict, and Scale. By examining the commonalities and differences across these reports, this integrated analysis aims to comprehensively understand the challenges and complexities associated with air pollution in these countries. The analysis will highlight shared concerns, unique circumstances, and potential areas for improvement in addressing this pressing environmental issue.

The structure of this report mirrors the sections analyzed from the individual country reports:

- Complexity

This section delves into the intricate nature of air pollution, examining the multitude of variables influencing the problem, their interdependencies, the level of understanding surrounding the issue, the non-linearity of cause-and-effect relationships, and the ambiguity involved.

- Uncertainty

This section examines the commonalities and differences in how each country report characterizes the uncertainties associated with air pollution, encompassing predictability, rate of change, ambiguity, and risk of negative outcomes.

- Conflict

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This section analyzes the commonalities and differences in how each country report addresses the conflict dimensions of air pollution, focusing on stakeholder dynamics, interests, values, power imbalances, communication patterns, and levels of trust.

- Scale

This section explores the commonalities and differences in how these reports characterize the spatial and temporal scope of air pollution, its impact, and its reversibility.

Through this comparative approach, the report aims to contribute valuable insights for policymakers, researchers, and stakeholders working towards effective and sustainable solutions to mitigate air pollution and its adverse impacts on public health, the environment, and the economy.

2. Dimensions of wicked problems

2.1. Complexity

The sources discuss air pollution as a complex issue in Bulgaria, the Czech Republic, Greece, and North Macedonia. All four countries experience this environmental challenge, and the reports utilize the Wicked Problem Matrix to analyze the complexity and discusses the commonalities and differences in the Complexity section of the reports.

2.1.1. Number of variables influencing the problem

All four reports identify a high number of variables influencing air pollution in each country. They all highlight similar variables, including emission sources, meteorological factors, geographic and climatic conditions, and socio-economic factors.

- Emission sources: The reports consistently identify a variety of sources contributing to air pollution. These sources commonly include industrial activities, transportation, residential heating, agriculture, and waste management. Each report highlights specific emission sources relevant to its country's context. For example, the Bulgaria report mentions industrial activities and vehicle emissions as key contributors, while the Czech Republic report emphasizes the role of outdated household heating systems burning solid fuels. The Greece report highlights significant sourresidential heating using biomass and transboundary pollution. The North Macedonia report identifies energy production, particularly from lignite-fired power plants, as a major contributor.

- Meteorological factors: All four reports recognize the significant influence of meteorological conditions on air pollution levels. Factors such as wind patterns, temperature inversions, and precipitation play a crucial role in dispersing or concentrating pollutants. The Bulgaria report explicitly mentions the impact of meteorological conditions on pollutant dispersion and the challenges in predicting air pollution due to rapidly changing weather patterns.
- Geographic and climatic conditions: The reports acknowledge that a country's geographical location, topography, and climate patterns can influence air pollution. For instance, the Bulgaria report states that air pollution is a national and international issue due to transboundary pollution. The Czech Republic report highlights the impact of neighboring countries' emissions on air quality. The Greece report emphasizes the role of the country's location, topography, and regional climate patterns on pollutant transport and concentrations. The North Macedonia report points out that Skopje's location in a valley, with specific wind patterns and temperature inversions, exacerbates pollutant buildup.
- Socio-economic factors: The reports acknowledge the role of socio-economic factors, such as population density, economic activities, and energy consumption patterns, in contributing to air pollution. The Bulgaria report mentions the impact of population density in urban areas and individual choices regarding transportation and heating. The Czech Republic report discusses how socio-economic factors impact air pollution through the use of outdated and inefficient heating systems in households. Similarly, the Greece report highlights the influence of economic recession and energy poverty on the use of polluting fuels. The North Macedonia report identifies population growth and urbanization as factors that increase energy demand and influence fuel choices.

In addition to these common variables, the North Macedonia report introduces governance and institutional factors as a key variable influencing air pollution. This report emphasizes the importance of adequate coordination and communication among institutions, data availability, monitoring systems, and enforcement of regulations in effectively managing air quality.

2.1.2. Interdependencies between variables

The reports consistently highlight the high interdependency between the variables influencing air pollution. They all emphasize the interconnected nature of the factors and their combined effect on air quality.

- Emissions and meteorology: All four reports emphasize the dynamic interaction between emission sources and meteorological conditions. The Bulgaria report

discusses how changes in one variable can trigger a cascade of effects on others, making it difficult to isolate the impact of a single variable. The Czech Republic report notes how the effectiveness of emissions fees depends on the stringency of Best Available Technologies (BAT) standards and how weather conditions influence the conversion of emissions into exposure. The Greece report explains how wind patterns and atmospheric stability affect the dispersion or concentration of pollutants. The North Macedonia report illustrates how Skopje's topography and meteorological conditions interact with emissions, leading to severe pollution episodes.

- Policy and socioeconomic factors: The reports acknowledge the connection between policy decisions and socioeconomic factors in addressing air pollution. They emphasize that policies aimed at reducing emissions, such as promoting renewable energy, are influenced by economic conditions, public acceptance, and technology affordability. The Bulgaria report mentions how stricter emission standards can impact vehicle prices and consumer choices. The Czech Republic report discusses how the impact of household emissions on air pollution is influenced by population density and topographical features. The Greece report illustrates how policies to reduce emissions can be affected by economic conditions and the affordability of cleaner technologies. The North Macedonia report notes that urbanization drives energy demand, influencing choices between cleaner and polluting fuels.
- Transboundary pollution: The reports acknowledge the transboundary nature of air pollution and its impact on air quality in neighboring countries. This highlights the need for international cooperation and coordinated efforts to address the issue effectively.

The reports also highlight other important interdependencies:

- Governance and emission control: The North Macedonia report emphasizes the link between effective governance and emission control. It argues that strong institutions, efficient regulations, and proper enforcement are crucial to reducing emissions from different sectors.
- Climate change and air pollution: The North Macedonia report connects climate change and air pollution, explaining how climate change alters weather patterns, potentially exacerbating air pollution and its health impacts.
- Data availability and policymaking: The North Macedonia report underscores the importance of data in crafting effective policy. It suggests that accurate information on emissions, air quality, and source contributions are essential for developing targeted policies and measures.

2.1.3. Level of understanding of the problem

The reports present a moderate level of understanding of the air pollution problem, acknowledging both the established scientific knowledge and the existing gaps in comprehending the complexities.

- Concrete level of understanding: The reports provide concrete data on pollutant concentrations, health impacts, emission sources, and the effectiveness of implemented measures. The Bulgaria report cites specific data on pollutant concentrations, health impacts, and the origins of pollutants. The Czech Republic report mentions the observable aspects of air pollution, such as smog and air quality readings, but emphasizes the need for conceptual knowledge to understand its causes and solutions. The Greece report acknowledges the well-established science of air pollution but highlights the complexity arising from interactions between sources, meteorological conditions, and geographical factors. The North Macedonia report provides a clear understanding of the major pollutants, their health impacts, and tangible evidence of pollution levels from monitoring data.
- Conceptual level of understanding: The reports recognize the intricate relationships between different factors influencing air pollution and the need for a conceptual understanding of the problem. The Bulgaria report emphasizes the need for a conceptual grasp of atmospheric chemistry, meteorology, and societal influences to understand air pollution. The Czech Republic report similarly emphasizes the need for conceptual knowledge to understand the interaction between human activities, natural systems, and economic and political considerations. The Greece report acknowledges the complexity arising from the interaction of various factors and the ongoing research efforts to understand these interrelationships. The North Macedonia report recognizes the interplay between emissions, geography, meteorology, and socio-economic factors, acknowledging the complexity of managing air quality in a dynamic urban environment.

However, the reports also acknowledge that there are **limitations to the theoretical understanding** of air pollution. The North Macedonia report, in particular, calls for further research to fully understand the long-term impacts of climate change on air quality, the effectiveness of specific policy interventions, and the complex interactions within the system.

2.1.4. Linearity of cause-and-effect relationship

The reports highlight the non-linearity of the cause-and-effect relationship in air pollution, recognizing that a single action doesn't always lead to a directly proportional improvement in air quality.

- Complex interactions and feedback loops: The reports discuss how emissions from various sources interact with meteorological conditions and atmospheric chemistry, leading to complex and unpredictable pollution patterns. They emphasize the presence of feedback loops, where air pollution can impact climate change, further influencing weather patterns and air quality. The Bulgaria report explains how a single action, like reducing emissions from one industry, might not lead to a proportional improvement in air quality due to other factors like weather conditions or emissions from other sources. The Czech Republic report similarly states that the cause-and-effect relationship is difficult to understand due to complex interactions between pollutants and sources. The Greece report points out that the impact of emissions on air quality isn't directly proportional and can be significantly modified by meteorological conditions and the presence of other pollutants. The North Macedonia report highlights the interaction between climate change and air pollution, where emissions can influence weather patterns and further impact air quality.
- Non-linear response to emission Reductions: The reports acknowledge that a reduction in emissions doesn't always translate into a proportional decrease in pollutant concentrations. They attribute this non-linearity to complex atmospheric processes, the formation of secondary pollutants, and the influence of external factors.

2.1.5. Ambiguity and difficulty in understanding the problem

The reports express a moderate to high level of ambiguity in understanding air pollution due to data gaps, complex interactions between variables, and the evolving nature of the problem.

- Data gaps and uncertainties: The reports identify the limitations in data availability, monitoring capabilities, and the accuracy of emission inventories, which contribute to ambiguity in understanding the problem. For instance, the Bulgaria report mentions the need for more precise data on the interaction between social factors and air pollution. The Czech Republic report emphasizes the need for robust monitoring and data collection efforts to improve understanding. The Greece report points out uncertainties in estimating emissions from various sources. The North Macedonia report points to limited data

availability for specific pollutants and time periods as a significant challenge for comprehensive analysis.

- Complex interactions and evolving context: The reports acknowledge that fully comprehending the interplay between various factors and predicting the long-term impacts of interventions remains challenging. The Bulgaria report highlights the intricate interactions between variables and the need for further research to illuminate the problem's complexities. The Czech Republic report similarly emphasizes the evolving nature of air pollution and the presence of contaminated sites with unknown risks. The Greece report mentions the limitations of modeling in capturing the complexities of atmospheric processes. The North Macedonia report acknowledges the difficulty in understanding the complex interactions of contributing factors and predicting the long-term impacts of interventions, particularly in light of climate change, urbanization, and technological advancements.

In summary, all four reports recognize the complex and multi-dimensional nature of air pollution, highlighting similar challenges in understanding the intricate relationships between variables and predicting the effectiveness of interventions. They all emphasize the need for further research, robust data collection, and continuous monitoring to address the existing gaps in knowledge and improve air quality management strategies.

2.2. Uncertainty

All four reports analyzing air pollution in Bulgaria, Czech Republic, Greece, and North Macedonia present medium to high uncertainty across all four sub-categories: predictability, rate of change, ambiguity, and risk of negative outcomes. Each country uses a wicked problem matrix to categorize the different aspects of uncertainty in air pollution, allowing for a direct comparison across reports. The similarities across the different countries are:

2.2.1. Predictability

All four reports acknowledge the challenges in accurately predicting air pollution levels and their specific impacts. While models and data analysis provide a basis for understanding general trends, precise forecasting remains difficult due to the complex interplay of numerous factors.

- Meteorological variability: Unpredictable weather patterns like wind, temperature inversions, and precipitation significantly influence pollution levels and dispersion.

- Emission fluctuations: Emissions from various sectors (transportation, industry, domestic heating) fluctuate based on factors such as energy demand, economic activity, and behavioral patterns, adding to the difficulty of prediction.
- Implementation uncertainties: The effectiveness of even well-planned mitigation measures remains uncertain due to challenges in implementation, enforcement of regulations, and public acceptance.

2.2.2. Rate of change

The reports consistently highlight the dynamic nature of air pollution, acknowledging its susceptibility to rapid changes influenced by various factors.

- Urbanization and population growth: Rapid urbanization and population increases in cities escalate energy demand and traffic congestion, directly impacting emission levels.
- Climate change: Climate change introduces additional uncertainties by altering weather patterns, potentially exacerbating pollution episodes and influencing long-term trends.
- Technological advancements: The adoption of new technologies in both emission sources and pollution control can have unpredictable impacts on air quality.

2.2.3. Ambiguity

The reports express a moderate level of ambiguity regarding a complete understanding of air pollution, recognizing the need for further research to address knowledge gaps and data limitations.

- Data gaps: Limited data availability for certain pollutants, specific time periods, and source contributions hinders comprehensive analysis and accurate predictions.
- Model limitations: While atmospheric and dispersion models offer valuable insights, their reliance on assumptions and simplifications introduces uncertainty.
- Conflicting information: Differing perspectives on the severity of the problem or the effectiveness of certain measures contribute to the ambiguity and complicate decision-making.

2.2.4. Risk of negative outcomes

All reports emphasize the high risk of severe negative consequences associated with air pollution, underscoring the urgency of action.

- Public health impacts: Air pollution contributes significantly to respiratory and cardiovascular diseases, premature mortality, and other health issues, imposing substantial economic and social costs.
- Environmental degradation: Air pollution negatively impacts ecosystems, biodiversity, water quality, and contributes to climate change, with potential long-term and irreversible consequences.
- Economic costs: Pollution-related health impacts lead to increased healthcare expenditures, reduced productivity, lost workdays, and damage to infrastructure, affecting economic stability.

Despite these commonalities, certain distinctions emerge regarding the specific uncertainties highlighted and their perceived levels:

- Bulgaria: The report emphasizes the uncertainty associated with predicting meteorological conditions and their impact on pollution dispersion. It also acknowledges limitations in understanding the interplay of social factors and air pollution, particularly regarding citizen access to information.
- Czech Republic: This report focuses on uncertainties related to identifying the dominant sources of pollution and the precise contributions of different sectors. It highlights the need for more robust monitoring and data collection to address these knowledge gaps.
- Greece: The report emphasizes the challenges in understanding the specific causes and effects of air pollution in a particular location due to the complex interaction of emission sources, meteorological conditions, and atmospheric chemistry. It also acknowledges data limitations and research gaps as contributors to the ambiguity surrounding air pollution.
- North Macedonia: This report focuses on the uncertainties associated with implementing mitigation measures and their effectiveness due to challenges in enforcement, public acceptance, and technological advancements. It also acknowledges data gaps, particularly for specific pollutants and periods, which hinder comprehensive analysis.

These variations in emphasis likely stem from each country's specific circumstances, data availability, and research priorities. Recognizing these differences is crucial for developing tailored and context-specific strategies to address the uncertainties associated with air pollution effectively.

2.3. Conflict

This section analyzes the Conflict sections of four air pollution reports focusing on Bulgaria, the Czech Republic, Greece, and North Macedonia. It explores the commonalities and differences in how these reports address the conflict dimensions of air pollution, focusing on stakeholder dynamics, interests, values, power imbalances, communication patterns, and levels of trust. First, the commonalities are presented and then the differences.

2.3.1. Number of stakeholders

All four reports acknowledge the involvement of a diverse and substantial number of stakeholders in air pollution issues. These stakeholders include:

- Government institutions: Ministries and agencies responsible for environmental protection, energy, health, and local governance are invariably involved in developing and implementing air quality management strategies.
- Industries: Sectors like energy production, manufacturing, transportation, and waste management are recognized as significant emission sources and are impacted by regulations and mitigation measures.
- Civil society organizations: Environmental NGOs and community groups play a vital role in advocating for improved air quality, representing citizen concerns, and influencing policy-making.
- Citizens: The entire population is affected by air pollution, albeit to varying degrees depending on factors such as location, socioeconomic status, and health vulnerabilities.

2.3.2. Alignment of interests and values

While a shared interest in clean air and a healthy environment exists, the reports reveal misalignments in priorities and approaches among stakeholders, leading to potential conflicts.

- Economic growth vs. Environmental protection: The need for economic development, particularly in industries contributing to emissions, often clashes with environmental regulations and the push for cleaner technologies.

- Short-term costs vs. Long-term benefits: Implementing effective mitigation measures frequently requires significant upfront investments and economic adjustments, which can conflict with short-term economic gains.
- Individual behavior vs. Collective action: Encouraging behavioral changes, like reducing private vehicle usage or switching to cleaner heating options, can face resistance due to personal convenience, cost constraints, or a lack of awareness.

2.3.3. Power imbalances

The reports indicate uneven power dynamics among stakeholders, often hindering equitable and effective decision-making.

- Government influence: Governments typically wield significant power in setting regulations, enforcing standards, and allocating resources. However, their effectiveness depends on political will, institutional capacity, and financial resources, which can vary considerably.
- Industry lobbying: Industries, particularly those with substantial economic influence, can pressure policymakers to prioritize economic interests over stricter environmental regulations.
- Limited citizen participation: While citizens are most directly affected by air pollution, their power to influence decisions often hinges on their capacity to organize, advocate effectively, and hold decision-makers accountable.

Despite these shared challenges, differences emerge regarding the specific conflicts highlighted and their perceived intensity:

- Bulgaria: The report emphasizes the limited trust between citizens and authorities, attributing it to perceived inaction and inadequate responses from authorities to address air pollution concerns. This lack of trust may stem from the imbalanced power dynamics, where the national government and industry hold more sway.
- Czech Republic: This report highlights potential conflicts related to the implementation costs and timelines of emission reduction measures, suggesting potential tensions between regulatory goals and industry preferences. Information asymmetry between firms and the government regarding the costs of adopting environmentally friendly technologies is also highlighted as a potential source of conflict.
- Greece: The reports primarily address technical aspects of air pollution, with limited exploration of stakeholder perspectives and potential conflicts. The need

for a comprehensive stakeholder analysis to identify specific interests and potential conflicts is emphasized.

- North Macedonia: This report explicitly addresses the conflict between economic growth and environmental protection, acknowledging the challenges in balancing industrial development with the need for cleaner practices. It also highlights the need for improved communication and trust-building to address information gaps and transparency challenges that hinder stakeholder collaboration.

Analyzing these specific conflict dynamics is essential for developing tailored strategies to mitigate tensions, promote collaboration, and ensure more equitable and effective air quality management.

2.4. Scale

This section analyzes the Scale sections of four air pollution. It explores the commonalities and differences in how these reports characterize the scale of air pollution, encompassing spatial and temporal dimensions, levels of impact, the number of affected individuals and organizations, and the reversibility of consequences.

Commonalities identified in the reports are

2.4.1. Spatial impact

All reports acknowledge that air pollution is a transboundary issue extending beyond national borders, impacting neighboring countries and requiring international cooperation for effective mitigation. While the reports primarily focus on national and regional implications, they consistently highlight the uneven distribution of pollution, with urban centers and industrial regions experiencing higher levels than rural areas.

2.4.2. Temporal scale

The reports emphasize the long-term and persistent nature of air pollution. They analyze historical emission trends dating back several decades, indicating that the problem is not recent and has accumulated over time. Furthermore, the reports consistently project future challenges, recognizing that even with ambitious mitigation measures, the impacts of air pollution will continue for several decades.

2.4.3. Impact level

The reports consistently highlight the severe and wide-ranging negative impacts of air pollution across multiple domains:

- Human health: Air pollution is unequivocally linked to respiratory diseases, cardiovascular problems, increased mortality rates, and various other health issues, imposing a significant burden on healthcare systems and overall well-being.
- Ecosystems: Air pollution contributes to acidification, eutrophication, damage to vegetation, and biodiversity loss, impacting natural ecosystems and their vital services.
- Economic costs: Pollution-related health impacts lead to increased healthcare expenditures, reduced productivity, lost workdays, and damage to infrastructure, affecting economic stability and development.

2.4.4. Number affected

The reports consistently indicate that air pollution affects a vast number of people and organizations:

- General population: The reports express concerns for the health and well-being of the entire population, with particular attention to vulnerable groups like children, the elderly, and those with pre-existing health conditions.
- Industries: Various sectors, particularly those contributing to emissions, are subject to regulations, economic impacts, and the need to transition towards cleaner technologies.
- Government agencies: Multiple government agencies are involved in managing and mitigating air pollution, demanding coordination, resources, and effective policy-making.

2.4.5. Reversibility

While acknowledging the potential for mitigation through emission reductions and technological advancements, the reports express a degree of caution regarding the **irreversibility of certain impacts**, particularly those related to:

- Long-term health consequences: Chronic health conditions and premature mortality from prolonged exposure to air pollution can have lasting and often irreversible effects on individuals and communities.

- Climate change contributions: Air pollution contributes to climate change, which has far-reaching and potentially irreversible consequences for global ecosystems and human societies.

Despite these commonalities, some distinctions emerge regarding the specific aspects of scale emphasized in each report:

- Bulgaria: The report highlights the national scale of the problem, emphasizing its impact on public health and the environment across the country. It also acknowledges the transboundary nature of air pollution, referencing studies on pollution in border regions.
- Czech Republic: This report focuses on the multi-level spatial scale of air pollution, from international agreements and collaborations to national policies, regional variations, and local pollution hotspots within cities. It also emphasizes the long-term persistence of the problem, analyzing historical trends and setting targets for future emission reductions.
- Greece: The report highlights the regional differences in pollution levels, referencing varying PM2.5 concentrations across Greek cities. It also discusses the national and regional impacts of air pollution on specific areas like Thessaloniki and rural Crete. The report underscores the high impact of air pollution on health, the environment, and the economy, emphasizing its significant consequences.
- North Macedonia: This report explicitly states that air pollution is a national problem impacting cities and urban centers across the country. It highlights pollution hotspots in all areas and emphasizes that even the average exposure to PM2.5 exceeds WHO guidelines.

These variations in emphasis likely reflect differences in the scope and focus of each report, the availability of data at different spatial scales, and the specific concerns and priorities within each country. Understanding these specifics in scale is crucial for developing targeted interventions, allocating resources effectively, and fostering collaborative efforts to address the multifaceted challenges of air pollution.

3. Strategies

As air pollution presents a significant environmental and public health challenge across Europe, impacting countries like Bulgaria, the Czech Republic, Greece, and North

Macedonia. These nations are actively implementing various strategies to mitigate air pollution and improve air quality for their citizens. While each country faces unique circumstances and adopts tailored approaches, there are notable commonalities and differences in their strategies for combating this complex issue.
This report provides a comparative analysis of the strategies employed by these four countries, drawing on information from individual country reports and a previous conversation summarizing those reports. The analysis is divided into two key sections: Analysis of existing strategies and actions and proposed strategies and activities.

3.1. Analysis of existing strategies and actions

This section examines the current approaches taken by each country to address air pollution, including their methods for breaking down the problem, identifying stakeholders, fostering collaboration, prototyping solutions, implementing adaptive management practices, and promoting transparency.

3.1.1. Breaking down the problem

All four countries employ a sectoral approach to break down the complex issue of air pollution. They target key polluting sectors and implement tailored interventions.

- Domestic heating: Programs promoting cleaner heating technologies, subsidies for cleaner alternatives like pellet stoves, heat pumps, and gas boilers, regulations on solid fuel burning, and energy efficiency improvements in buildings are common strategies.
- Transportation: Promoting public transportation, implementing stricter vehicle emission standards, encouraging fuel switching to cleaner alternatives, introducing vehicle scrappage programs, and investing in cycling and pedestrian infrastructure are common tactics.
- Industry: Enforcing emission limits for industrial facilities, promoting the adoption of cleaner production technologies, offering financial incentives for pollution control investments, and supporting research and development of innovative solutions are widely adopted strategies.
- Waste management: Improving waste collection and treatment systems, promoting recycling and waste reduction, controlling emissions from landfills and waste incineration, and tackling illegal waste burning are key actions.
- Geographic focus: Recognizing the uneven distribution of pollution, countries prioritize interventions in pollution hotspots and heavily polluted urban areas. Air quality improvement plans are often developed for specific cities or regions.

3.1.2. Identifying stakeholders

All reports acknowledge the importance of stakeholder engagement in air pollution management, though the level of detail and analysis varies.

- Intersectoral groups and committees: Establishing groups with representatives from government agencies, industry, civil society, and research institutions to foster dialogue, coordinate actions, and share knowledge is a common approach.
- Public consultations: Engaging citizens and communities through public forums, surveys, and online platforms during the development and implementation of air quality plans is recognized as crucial for ensuring public support and local ownership.

3.1.3. Collaboration

International cooperation is emphasized in all reports, particularly within the European Union framework.

- EU directives and funding: Countries leverage EU directives on air quality, emission standards, and funding mechanisms to support their national efforts.
- Transboundary air pollution agreements: Participating in international agreements and joint research projects to address transboundary air pollution is crucial.
- Cross-border collaboration: Collaborating with neighboring countries to share knowledge, harmonize policies, and monitor pollution levels in border regions is recognized as important.

3.1.4. Prototyping solutions

While not explicitly labeled as such, many countries implement pilot projects and test various measures before nationwide implementation.

- Pilot projects: Implementing pilot air quality improvement programs in specific cities or regions allows for testing different strategies, evaluating their effectiveness, and gathering valuable data before scaling them up.
- Subsidy programs: Introducing subsidies for cleaner heating technologies, electric vehicles, or energy efficiency upgrades allows for assessing public uptake, cost-effectiveness, and emission reduction potential.

- Modeling and forecasting tools: Utilizing air quality models and forecasting systems to simulate the impact of different emission reduction scenarios aids in evaluating potential strategies and informing decision-making.

3.1.5. Adaptive management

The reports acknowledge the need for flexible and adaptive approaches to air pollution management, recognizing the evolving nature of the problem.

- Regular review and revision: Air quality plans are typically reviewed and revised periodically based on monitoring data, emission trends, and lessons learned from implementation.
- Data-driven decision-making: Emphasizing the importance of data collection, analysis, and monitoring to inform adaptive management strategies is essential.

3.1.6. Transparency

Countries generally strive for transparency in air quality management by publicly available data and information.

- Publicly available data: Air quality monitoring data, emission inventories, and reports on air quality trends are often accessible to the public through websites, online platforms, or dedicated apps.
- Progress reporting: Regular reporting on the progress of air quality improvement efforts to national parliaments, the European Commission, and other relevant bodies ensures accountability and transparency.

3.2. Proposed strategies and activities

Building upon the analysis of existing efforts, this section explores proposed strategies and activities to enhance air pollution mitigation in these countries. This includes recommendations for improved stakeholder engagement, strengthened regulatory frameworks, promotion of sustainable solutions, empowerment of local communities, and fostering a culture of environmental responsibility.

3.2.1. Enhanced stakeholder engagement

Recognizing the limitations of current engagement efforts, the reports propose deepening stakeholder involvement.

- Multi-stakeholder platforms: Establishing permanent platforms for dialogue and collaboration among government agencies, industries, civil society organizations, and citizens to ensure ongoing communication and coordinated action.
- Meaningful public participation: Creating mechanisms for genuine public input at all stages of policy development, from identifying problems and setting priorities to designing solutions and monitoring progress.
- Capacity building: Providing training, resources, and support to local communities, citizen groups, and NGOs to empower them to participate in air quality management actively.

3.2.2. Strengthening regulatory framework and enforcement

The reports highlight the need for stricter regulations, robust enforcement mechanisms, and increased transparency in regulatory processes.

- Stricter emission standards: Aligning national emission limits for various sectors with EU standards and progressively tightening those standards to drive continuous improvement.
- Effective enforcement: Strengthen monitoring and inspection capacity, impose meaningful penalties for non-compliance, and make enforcement actions transparent and accountable.
- Transparency in regulation: Improving public access to information about industrial emissions, permit conditions, inspection reports, and enforcement actions to build trust and ensure industries are held accountable.

3.2.3. Promoting sustainable and affordable solutions

The reports emphasize the need to promote and incentivize sustainable technologies and practices that are affordable and accessible to all.

- Financial incentives: Expanding financial assistance and subsidies for households and businesses to adopt cleaner heating systems, energy efficiency measures, renewable energy sources, and electric vehicles.
- Green public procurement: Leveraging government purchasing power to create demand for cleaner products and technologies, stimulating innovation and market development.
- Investment in public transport: Investing in public transportation infrastructure, improving service quality, and making public transport more affordable and convenient to reduce reliance on private vehicles.

- Research and development: Supporting research and development of innovative air pollution control technologies, sustainable energy solutions, and cleaner production processes.

3.2.4. Empowering local communities

Recognizing the importance of place-based solutions, the reports propose empowering local governments and communities to take ownership of air quality improvement efforts.

- Local air quality plans**:** Supporting local governments in developing and implementing tailored air quality plans that address specific pollution sources and community concerns.
- Community-based initiatives: Encouraging and supporting community-led initiatives to raise awareness, promote behavioral changes, monitor air quality, and implement local solutions.
- Decentralization and local ownership: Delegating authority and resources to local levels to ensure that air quality management is responsive to local needs and priorities.

3.2.5. Fostering a culture of environmental responsibility

The reports recognize that tackling air pollution requires a broader cultural shift towards environmental responsibility.

- Integrating air quality considerations: Ensuring that air quality considerations are integrated into all relevant policies and planning processes, including urban planning, transportation planning, industrial development, and energy policy.
- Public awareness campaigns: Launching comprehensive and targeted public awareness campaigns to educate citizens about the sources, impacts, and solutions to air pollution, emphasizing individual and collective responsibility for improving air quality.
- Education and behavior change: Integrating air quality and environmental education into school curricula and promoting behavior change initiatives to encourage sustainable lifestyles and choices.

4. Conclusion

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This integrated report examined the complex issue of air pollution in Bulgaria, the Czech Republic, Greece, and North Macedonia through the lens of the Wicked Problem Matrix. By analyzing the commonalities and differences across the four country reports, the analysis aimed to provide a comprehensive understanding of the challenges and complexities associated with air pollution in these countries.

The report highlighted key shared concerns across the four countries, including:

- the multitude of variables influencing air pollution and their intricate interdependencies,
- the uncertainties in predicting pollution levels and the effectiveness of interventions,
- the presence of conflicts among stakeholders with differing interests and power dynamics, and
- the significant spatial and temporal scale of the problem and its severe impacts on public health, ecosystems, and the economy.

Despite these shared challenges, each country report also revealed distinct characteristics and priorities, reflecting their specific circumstances, data availability, and policy approaches.

The report examined existing strategies employed by the four countries to mitigate air pollution, highlighting a common sectoral approach targeting key polluting sources like domestic heating, transportation, industry, and waste management. The analysis also explored proposed strategies and activities to enhance air pollution mitigation efforts, including strengthening regulatory frameworks, promoting sustainable solutions, empowering local communities, and fostering environmental responsibility.

Addressing air pollution effectively requires a long-term commitment, continuous adaptation, and collaboration among all stakeholders. By learning from each other's experiences, sharing best practices, and prioritizing a multi-faceted approach that acknowledges the wicked nature of the problem, these countries can make significant progress in improving air quality and safeguarding public health and the environment. This integrated report serves as a valuable resource for policymakers, researchers, and communities working towards a cleaner and healthier future for Bulgaria, the Czech Republic, Greece, and North Macedonia.

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2021-1-MK01-KA220-HED-000030188

EXPERIMENTATION REPORT

Mapping Bulgaria's Air Pollution on Wicked Problem Matrix

1. Introduction

Air pollution represents a significant environmental challenge in Bulgaria, characterized by its complexity and widespread impacts on human health, ecosystems, and economic activities. This report seeks to analyze the intricate nature of air pollution within the framework of the Wicked Problem Matrix. By evaluating the variables influencing air pollution, their interdependencies, and the non-linear cause-and-effect relationships, this report provides a comprehensive understanding of the issue's multidimensionality.

Drawing on data from a range of sources, the analysis addresses key factors such as emissions from various sectors, meteorological conditions, socioeconomic drivers, and the effectiveness of policy measures. Furthermore, it highlights the regional and national scale of the problem, emphasizing the long-term implications and the need for collaborative, adaptive, and transparent approaches to mitigation.

2. Dimensions of wicked problems

2.1. Complexity

Air pollution in Bulgaria is a complex and pressing issue, influenced by a wide range of natural and human-made factors. These factors create intricate interdependencies, making it challenging to fully understand and address the problem. By exploring the variables, interconnections, and levels of understanding involved in air pollution, this section aims to provide a comprehensive overview of the issue and highlight the key challenges it presents.

By evaluating these variables within the framework of complexity, this analysis seeks to provide a deeper understanding of the intricate dynamics at play in addressing air pollution in Bulgaria.

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2.1.1. Number of variables

High. Air pollution is influenced by a multitude of variables, encompassing both natural and human-made sources (Cherneva, 2023; Lee et al., 2021). The sources highlight the need for sophisticated mathematical models that can consider numerous factors to better understand and predict air pollution (Cherneva, 2023; Lee et al., 2021; European Commission, 2018).

- Factors include meteorological conditions, chemical processes, emissions from vehicles, industrial activities, and residential heating practices (Lee et al., 2021; European Commission, 2018; World Bank, 2020).
- The chemical composition of pollutants, their interactions, and their dispersion patterns further add to the complexity (Lee et al., 2021; World Bank, 2020).
- Social and economic aspects, like population density, urban planning, and individual choices regarding transportation and heating, also play significant roles (Lee et al., 2021; Cherneva, 2023; Deloitte, 2021; Ministry of Environment and Water, 2023; European Commission, 2018; World Bank, 2020).

2.1.2. Interdependencies between variables

High. The variables influencing air pollution are highly interconnected, creating intricate feedback loops (Lee et al., 2021).

The sources emphasize the link between population density in urban areas and air quality. Sofia's population growth and increasing vehicle use illustrate this connection (Lee et al., 2021; Deloitte, 2021). Implementing a low-emission zone in Sofia highlights these interdependencies, as its effectiveness depends on driver behavior, vehicle purchasing trends, and the availability of public transportation (Lee et al., 2021; European Commission, 2018).

Changes in one variable, like stricter emission standards for vehicles, can trigger a cascade of effects on other variables, such as the price of vehicles, consumer choices, and the overall impact on air quality (Lee et al., 2021; European Commission, 2018). The intricate web of interdependencies makes it difficult to isolate the impact of any single variable and necessitates a holistic approach to understanding and addressing air pollution (Lee et al., 2021; European Commission, 2018).

2.1.3. Level of understanding

Low and medium. The problem of air pollution can be understood at both concrete, observable levels and abstract, conceptual levels (Lee et al., 2021; Deloitte, 2021; Cherneva, 2023).

- **Concrete level:** The sources provide specific data on pollutant concentrations, health impacts, and the types and origins of pollutants (Lee et al., 2021; Deloitte, 2021; Cherneva, 2023). Measurements of PM10 and NOx emissions, for example, offer tangible evidence of the problem's scale (Lee et al., 2021; World Bank, 2020). Observations of respiratory problems and other health issues linked to air pollution provide concrete examples of its detrimental effects (Deloitte, 2021).
- **Conceptual level:** The sources delve into the intricate interplay of factors contributing to air pollution, requiring a conceptual grasp of atmospheric chemistry, meteorology, and societal influences (Cherneva, 2023; Lee et al., 2021; World Bank, 2020). Understanding how emissions from various sources combine with weather patterns to create smog episodes necessitates conceptual thinking (Lee et al., 2021; World Bank, 2020). Analyzing how policy interventions, such as low-emission zones, interact with economic factors and individual behavior demands a conceptual understanding of complex systems (Lee et al., 2021; World Bank, 2020).

2.1.4. Linearity of cause-and-effect

Medium. The cause-and-effect relationship in air pollution is non-linear and complex, characterized by feedback loops and interactions (Lee et al., 2021; World Bank, 2020).

A single action, like reducing emissions from a specific industry, doesn't always lead to a directly proportional improvement in air quality (Lee et al., 2021; World Bank, 2020). Other factors, like weather conditions or emissions from other sources, can moderate or amplify the impact of the initial action (Lee et al., 2021; World Bank, 2020). The non-linearity makes it challenging to predict the precise consequences of interventions and emphasizes the need for adaptive management strategies (Lee et al., 2021; World Bank, 2020).

2.1.5. Ambiguity and difficulty

Medium. The problem of air pollution is moderately ambiguous and requires a comprehensive understanding to unravel (Cherneva, 2023; World Bank, 2020). The sources provide a substantial amount of information, but gaps in knowledge remain, particularly regarding the complex interplay of social factors and air pollution (Cherneva, 2023; World Bank, 2020). For instance,

- Research on local government engagement with air pollution in Sofia acknowledges limitations in understanding how citizens access and interpret information (Cherneva, 2023; World Bank, 2020).
- The ambiguity arises from the intricate interactions between variables, the non-linear cause-and-effect relationships, and the need for further research to fully illuminate the problem's complexities (Lee et al., 2021; World Bank, 2020).

Conclusion

In conclusion, air pollution in Bulgaria is a multifaceted challenge that requires a holistic approach to research and mitigation. With numerous interdependent variables, non-linear cause-and-effect relationships, and moderate levels of ambiguity, addressing air pollution demands careful consideration of both concrete and conceptual factors. Effective solutions will depend on the integration of scientific data, policy interventions, and societal engagement to manage and reduce the impact of air pollution on public health and the environment.

2.2. Uncertainty

Uncertainty is a defining characteristic of wicked problems, reflecting the lack of knowledge, stability, and predictability surrounding both the problem and its potential solutions. Air pollution in Bulgaria presents significant uncertainty due to its complexity and the multitude of factors influencing it. From meteorological conditions to human behavior and policy changes, predicting and managing air pollution remains a challenge. This section explores the aspects of uncertainty related to air pollution, including predictability, rate of change, ambiguity, and the potential risks of negative outcomes.

This section explores these dimensions of uncertainty, evaluating the predictability of air pollution using models and data, the variability of pollution levels over time, and the inherent complexity and ambiguity in understanding the issue. Additionally, it examines the substantial risks posed by air pollution to human health, ecosystems, and economic stability. By addressing these factors, the analysis aims to provide a comprehensive understanding of the uncertainties that complicate efforts to mitigate air pollution in Bulgaria.

2.2.1. Predictability

High. Predicting air pollution levels in Bulgaria is challenging due to the multitude of influencing factors and their intricate interactions. The sources highlight the need for more precise mathematical models that consider numerous factors to better understand and predict air contamination processes (Zheleva, 2023).

- Meteorological conditions, such as wind patterns, temperature inversions, and precipitation, play a crucial role in pollutant dispersion and can shift rapidly. Unforeseen events, like wildfires or industrial accidents, can lead to sudden spikes in pollution levels, adding to the unpredictability.
- Human behavior, such as increased vehicle use during holidays or changes in heating practices, can also impact pollution levels in ways that are difficult to anticipate.
- Changes in emissions resulting from the implementation of Low Emission Zones are estimated by calculating fleet-average emission factors. The analysis, however, assumes a constant total vehicle activity, which may not accurately reflect reality. Compliance rates and driver behavior are also difficult to predict (Lee et al., 2021).

2.2.2. Rate of change

Medium. Air pollution levels can fluctuate significantly over various timescales, contributing to the difficulty in managing the problem.

- Short-term variations: Weather patterns can cause hourly or daily shifts in pollutant concentrations, leading to rapid changes in air quality. Traffic

congestion during peak hours can create localized pollution hotspots that dissipate as traffic volumes decrease.

- Seasonal variations: Increased residential heating during winter months can elevate PM emissions, particularly in areas reliant on solid fuels (Ministry of Environment and Water, 2019). Agricultural activities, such as fertilizer application or crop residue burning, can contribute to seasonal spikes in certain pollutants.
- Long-term trends: Population growth, urbanization, and economic development can lead to gradual increases in emissions from various sources over time. Policy interventions, such as stricter emission standards or the promotion of cleaner technologies, aim to mitigate these long-term trends but their effectiveness unfolds gradually.

The analysis of air quality in the Bulgaria–Romania trans-border area shows that air quality has improved over the past two decades, but pollutant levels still negatively affect human health and the environment (Zheleva, 2023).

2.2.3. Ambiguity

Medium. While the sources provide substantial information about air pollution in Bulgaria, there are still areas where further research is needed to gain a complete understanding. The use of expert judgment and proxy data to estimate emissions highlights the limitations in data availability and the potential for inaccuracies. The uncertainty associated with emission factors, particularly for certain industrial processes and waste management activities, adds to the ambiguity.
The complex interaction of social factors, economic development, and policy decisions creates challenges in fully comprehending the drivers and consequences of air pollution. Research on local government engagement with air pollution in Sofia acknowledges limitations in understanding how citizens access and interpret information (Cherneva, 2023).

2.2.4. Risk of negative outcomes

High. Air pollution poses significant risks to human health, ecosystems, and the overall well-being of the Bulgarian population.

- Health impacts: Particulate matter (PM), nitrogen dioxide (NO2), and ground-level ozone (O3) are recognized as the three pollutants that most significantly affect human health (Zheleva, 2023). The sources emphasize the link between air pollution and respiratory diseases, cardiovascular problems, and other health issues. Vulnerable populations, such as children, the elderly, and individuals with pre-existing health conditions, face heightened risks from air pollution exposure.
- Environmental impacts: Air pollution can damage vegetation, acidify water bodies, and contribute to climate change.
- Economic impacts: Healthcare costs associated with treating air pollution-related illnesses place a burden on the economy. Reduced agricultural yields due to air pollution can impact food security and livelihoods.

Conclusion

The uncertainty surrounding air pollution in Bulgaria highlights the need for a comprehensive and adaptive approach to managing the issue. While some variables can be predicted or mitigated, the intricate interactions between factors and the potential for sudden changes make it essential to continue research, improve monitoring, and develop flexible strategies to reduce risks and protect public health and the environment. This requires a combination of ongoing research, robust monitoring, adaptive management strategies, and proactive measures.

2.3. Conflict

Air pollution is a significant environmental issue in Bulgaria, affecting a wide range of stakeholders, from citizens and local governments to industries and civil society organizations. The sources of pollution, including industrial activities, residential heating, and vehicle emissions, pose substantial health risks and environmental challenges. In response, various stakeholders, such as national ministries, municipalities, research institutions, and NGOs, are engaged in addressing the issue through policy development, public awareness campaigns, and technological innovations. However, despite the growing recognition of the problem, there are significant conflicts surrounding air pollution, stemming from economic interests, political considerations, and gaps in communication between stakeholders. This paper explores the characteristics of the conflict surrounding air pollution in Bulgaria, including the number of stakeholders

affected, the alignment of their interests and values, the balance of power, communication challenges, and the level of trust between stakeholders. The conflict surrounding air pollution in Bulgaria exhibits the following characteristics:

2.3.1. Number of stakeholders affected

High. The sources demonstrate that air pollution in Bulgaria impacts a wide range of stakeholders, including:

- Citizens: They experience the direct health and well-being consequences of poor air quality (Cherneva, 2023; Cherneva, 2023).
- Local Governments: Municipalities bear the responsibility of implementing air quality improvement programs and navigating the complexities of enforcement (European Commission, 2018; European Commission, 2018; Georgieva, Hristova, Spassova, & Voynova, n.d.).
- National Government Ministries: Various ministries, such as the Ministry of Environment and Water, Ministry of Health, Ministry of Energy, and Ministry of Agriculture, Forestry and Food, play roles in policy development, regulation, and enforcement (European Commission, 2018; Ministry of Environment and Water, 2023).
- Industry: Industrial facilities, particularly those involved in energy production, manufacturing, and waste management, contribute significantly to air pollution and face pressure to reduce emissions (European Commission, 2018; Cherneva, 2023; Cherneva, 2023).
- NGOs and Civil Society: These groups advocate for cleaner air, raise public awareness, and often challenge government and industry practices (Cherneva, 2023; Cherneva, 2023; Georgieva, Hristova, Spassova, & Voynova, n.d.).
- Research Institutions: They conduct studies, provide data, and offer solutions for air quality management (European Commission, 2018; Georgieva, Hristova, Spassova, & Voynova, n.d.).
- Media: Media outlets shape public perception and influence the political discourse surrounding air pollution (Georgieva, Hristova, Spassova, & Voynova, n.d.; Cherneva, 2023).

2.3.2. Alignment of interests

Misaligned. The sources highlight conflicts of interest between different stakeholders. Economic interests often clash with environmental concerns. For example, industries may resist stricter emission standards due to perceived costs, while citizens demand cleaner air for their health (Cherneva, 2023). Municipalities may face challenges in balancing the need for economic development with the pressure to implement stringent air quality measures. The sources note a reluctance from some municipalities to adopt measures like Low Emission Zones due to potential economic and political ramifications (World Bank, 2020).

2.3.3. Alignment of values

Partially Aligned. While stakeholders may disagree on specific solutions or the pace of change, there appears to be a general recognition of the importance of clean air for public health and environmental protection (European Commission, 2018). The sources indicate that public awareness of air pollution and its health impacts has grown in recent years, leading to increased pressure on authorities to take action (Cherneva, 2023; Cherneva, 2023). The European Forum on Eco-innovation showcases a collaborative effort among municipalities, companies, and experts to promote cleaner technologies and improve air quality (European Commission, 2018).

2.3.4. Balance of Power

Imbalanced. The sources suggest an imbalance of power among stakeholders.

- National government ministries and industry often hold significant influence, while citizens and NGOs may struggle to have their voices heard (Georgieva, Hristova, Spassova, & Voynova, n.d.).
- Municipalities face pressure from both national authorities and their constituents, creating a challenging position (World Bank, 2020).

2.3.5. Communication between stakeholders:

Average. The sources indicate that communication between stakeholders is not consistently effective. There is a need for improved dialogue between national and local authorities, as well as with citizens and industry. The sources note that legal frameworks and air quality programs are sometimes adopted without proper consultation with stakeholders, leading to misunderstandings and implementation challenges (World Bank, 2020; World Bank, 2020). The media plays a role in amplifying public concerns but may not always provide balanced or constructive coverage of the issue (Georgieva, Hristova, Spassova, & Voynova).

2.3.6. Level of trust between stakeholders:

Medium. The sources suggest that trust between stakeholders is limited, particularly between citizens and authorities (Georgieva, Hristova, Spassova, & Voynova). This lack of trust may stem from perceived inaction or inadequate responses from authorities to address air pollution concerns (Cherneva, 2023). The sources highlight the importance of transparency and collaboration to build trust and facilitate effective solutions (World Bank, 2020; Georgieva, Hristova, Spassova, & Voynova, n.d.).

Conclusion

The conflict surrounding air pollution in Bulgaria is multifaceted, with a large number of stakeholders involved, each with distinct interests and values. While there is general agreement on the importance of clean air, the misalignment of interests, imbalanced power dynamics, and communication gaps hinder effective solutions. The limited trust between stakeholders, particularly between citizens and authorities, further complicates the implementation of air quality improvement measures. To address these challenges, it is crucial for stakeholders to engage in more transparent and collaborative dialogues, align their efforts, and prioritize the public health and environmental benefits of cleaner air. Only through coordinated action and sustained commitment can Bulgaria make meaningful progress in reducing air pollution and improving air quality for its citizens.

2.4. Scale

The scale of a wicked problem reflects the extent of its spatial, temporal, and societal impact. Understanding the scale is crucial for evaluating the breadth and depth of a

problem's effects, including the geographic areas it influences, the duration of its consequences, and the severity of its impacts on individuals, organizations, and ecosystems.

Air pollution in Bulgaria has become a significant issue, affecting both the national and international levels. With a long history of harmful emissions, the problem has widespread implications for public health, the environment, and the economy. This analysis draws upon various reports and studies to characterize the scale, persistence, and impact of air pollution in the country, as well as the potential for mitigation through policy changes and technological advancements.

2.4.1. Area affected

National: The sources consistently focus on air pollution as a significant concern across Bulgaria. The National Inventory Report (Ministry of Environment and Water, 2023) meticulously documents greenhouse gas emissions from various sectors across the country. Reports on air quality improvement programs and health impacts (Health Effects Institute, 2022) further emphasize the nationwide scale of the problem.

International: Sources acknowledge the transboundary nature of air pollution. A study examines air pollution in the Bulgarian part of the Bulgaria-Romania trans-border area (Zheleva, 2023). The European Forum on Eco-innovation (European Commission, 2018) includes presentations on air quality solutions from various European countries, highlighting the shared challenges and collaborative efforts to address air pollution across national borders.

2.4.2. Time length affected

Long-Term: The sources emphasize the persistent and enduring nature of air pollution in Bulgaria. The National Inventory Report (Ministry of Environment and Water, 2023) provides a historical overview of greenhouse gas emissions, dating back to 1988, indicating that air pollution has been a long-standing challenge. Discussions of coal power plant decommissioning scenarios extend to 2038, suggesting that even with accelerated phase-out plans, the impacts of coal-based energy production will continue for several decades. The analysis of air quality trends and health impacts (Health Effects Institute, 2022) points to the long-term consequences of prolonged exposure to air pollution, including chronic diseases and premature mortality.

2.4.3. Level of impact

High. The sources consistently highlight the severe impacts of air pollution in Bulgaria. A study (Zheleva, 2023) emphasizes that "pollutant levels still show significant adverse effects on human health and the environment." The sources point to the significant health burden associated with air pollution (Health Effects Institute, 2022), linking it to respiratory diseases, cardiovascular problems, and premature mortality. The impact on career decisions of the highly-skilled workforce in Sofia underscores the economic and social consequences of poor air quality (Deloitte, 2021).

2.4.4. Number of people or organizations affected

High. The sources consistently indicate that air pollution affects a vast number of people and organizations in Bulgaria. The widespread health impacts (Health Effects Institute, 2022; Zheleva, 2023) suggest that a substantial portion of the population is affected by poor air quality. The involvement of multiple government ministries, research institutions, and NGOs (Ministry of Environment and Water, 2023; European Commission, 2018; Georgieva, Hristova, Spassova, & Voynova, n.d.) in addressing air pollution reflects the problem's extensive reach across various sectors of society.

2.4.5. Reversibility

Partly Reversible. While the sources acknowledge the long-term consequences of air pollution, they also suggest that mitigation efforts can lead to improvements in air quality. The discussion of coal power plant phase-out scenarios and eco-innovation initiatives (European Commission, 2018) highlights the potential to reduce emissions and improve air quality through policy changes and technological advancements. The National Air Quality Improvement Program (Ministry of Environment and Water, 2023) outlines measures aimed at reducing emissions from various sectors, indicating a commitment to addressing the problem. However, sources also recognize that certain impacts, such as chronic health conditions resulting from prolonged exposure to air pollution, may be irreversible.

Conclusion

Air pollution in Bulgaria remains a critical challenge, with severe and lasting consequences for public health, the environment, and society. Despite the significant

impacts, efforts to reduce emissions through national programs and international collaboration offer a path toward improvement. While some effects may be irreversible, proactive measures and innovations in air quality management can help mitigate the problem over time.

3. Strategies

Addressing wicked problems requires a structured approach that connects real-world strategies to established frameworks for problem-solving. The wicked problems matrix provides a set of strategies—breaking the problem down, identifying stakeholders, fostering collaboration, prototyping solutions, adopting adaptive management, and ensuring transparency—that can be used to tackle complex and interconnected challenges.

This section aims to identify strategies discussed in the source data and map them to the wicked problems matrix framework. By analyzing and aligning real-world approaches to these structured strategies, the section provides insights into how existing actions can be enhanced to better address the multifaceted nature of air pollution in Bulgaria. This mapping process helps to evaluate the effectiveness of current measures and identify gaps that need to be addressed for comprehensive and sustainable problem-solving.

3.1. Break the problem down

- **Identify specific sources**: The sources emphasize the importance of pinpointing major sources of air pollution. The INNOAIR Guidebook breaks down sources into sectors like transport, industry, domestic heating, and agriculture, allowing for targeted interventions (Georgieva, Hristova, Spassova, & Voynova, n.d.). Studies pinpoint specific culprits in Sofia, such as domestic heating with solid fuels and public transport emissions, guiding localized solutions (European Commission, 2018).
- **Focus on key pollutants**: Recognizing that certain pollutants pose greater health risks, sources call for prioritizing action. Sofia's air quality improvement program focuses on tackling PM10, the most pressing pollutant in the city (European Commission, 2018). National and international reports consistently highlight the dangers of PM2.5, NO2, and ozone (Health Effects Institute, 2022).

- **Address spatial variations**: Sources acknowledge the uneven distribution of air pollution, necessitating location-specific solutions. Studies use advanced modeling techniques to analyze pollution patterns at various scales, from the regional level down to specific neighborhoods within cities (Zheleva, 2023; Georgieva et al., 2021). The use of satellite data and local air quality management systems enables a more granular understanding of pollution hotspots and informs targeted interventions (Georgieva et al., 2021).

3.2. Identify stakeholders

- **Engage a wide range of actors**: Sources consistently recognize the need to involve diverse stakeholders in the solution process. The European Forum on Eco-innovation brings together municipalities, companies, experts, and citizens to discuss solutions (European Commission, 2018). Studies emphasize the role of NGOs and civil society in raising awareness and advocating for cleaner air (Cherneva, 2023). The INNOAIR Guidebook stresses the importance of involving citizens at all levels of the process (Georgieva et al., n.d.).
- **Understand interests and values**: Sources highlight the diverse and sometimes conflicting interests at play. The need for economic development often clashes with the urgency of environmental protection, creating tension between industry, government, and citizens (Cherneva, 2023). Municipalities face the challenge of balancing national air quality targets with local economic and political considerations (Cherneva, 2023; Georgieva et al., 2021). Understanding these diverse perspectives is crucial for crafting solutions that address concerns and foster cooperation.

3.3. Collaborate

- **Foster multi-level governance**: Sources advocate for collaborative approaches that bridge national, regional, and local levels. Experts call for coherence in policy at local and national levels, ensuring that national air quality plans are co-developed with cities (Cherneva, 2023). The EU's role in setting air quality standards and providing funding mechanisms for improvement programs underscores the importance of cross-border collaboration (Georgieva et al., n.d.; Cherneva, 2023).

- **Promote public-private partnerships**: Sources highlight the potential of joint efforts between government, industry, and research institutions. Public procurement can boost demand for cleaner technologies, driving innovation and creating economies of scale (European Commission, 2018). The European Forum on Eco-innovation showcases successful examples of public-private partnerships in developing and deploying air quality solutions (European Commission, 2018).

3.4. Prototype solutions

- **Pilot projects and case studies**: Sources advocate for testing and evaluating different approaches before widespread implementation. Sofia's pilot project to introduce filters in households provides valuable insights for scaling up solutions (European Commission, 2018). The European Forum on Eco-innovation showcases 37 case studies of successful air quality initiatives, offering models for replication (European Commission, 2018).
- **Modeling and forecasting tools**: Sources emphasize the role of sophisticated tools in assessing the effectiveness of different strategies. The Bulgarian Chemical Weather Forecast System and local air quality management systems (LAQMS) allow for simulating the impact of emission reduction scenarios, aiding in informed decision-making (Marinov, Petrova-Antonova, & Malinov, 2022). The use of time series analysis and forecasting models enables a better understanding of pollution trends and the potential impact of various interventions (Marinov et al., 2022; Pant et al., 2023).

3.5. Adaptive management

- **Flexibility and continuous improvement**: Sources recognize the need for adaptable strategies that can evolve with new knowledge and changing circumstances. The INNOAIR Guidebook calls for multifaceted research and joint efforts by experts to address the evolving nature of air pollution (Georgieva et al., n.d.). The emphasis on scientific monitoring, data collection, and analysis underscores the importance of continuous evaluation and adjustment of strategies (Georgieva et al., 2021; Zheleva, 2023). Adaptive management principles are crucial for navigating the complexities of air pollution and responding to unexpected challenges or opportunities.

3.6. Be transparent

- **Open communication and public engagement**: Sources highlight the importance of clear and accessible information to build public trust and support. Sofia's development of an early warning system that informs citizens about daily pollution levels demonstrates a commitment to transparency (European Commission, 2018). The emphasis on public awareness campaigns and citizen engagement in decision-making processes underscores the need to foster open dialogue and address public concerns (Cherneva, 2023; Georgieva et al., n.d.).

4. Proposed strategies and activities

Building on the strategies identified above and drawing on the specific context of Bulgaria, the following concrete actions could contribute to solving the air pollution problem:

- **Accelerate the transition to renewable energy**: Prioritize the phase-out of coal power plants, setting ambitious timelines and providing support for affected communities and workers. Invest heavily in renewable energy sources, such as solar, wind, and geothermal, leveraging EU funding mechanisms and attracting private investments. Promote energy efficiency measures in buildings and industries, reducing energy demand and emissions.
- **Modernize transportation systems**: Expand and improve public transportation networks, particularly in major cities, making them more accessible, affordable, and reliable. Invest in electric vehicle charging infrastructure and incentivize the adoption of electric vehicles through subsidies and tax breaks. Promote cycling and walking as sustainable modes of transport, developing safe and dedicated infrastructure. Consider implementing congestion charging schemes in highly polluted urban areas to discourage private vehicle use.
- **Tackle domestic heating emissions**: Implement stricter regulations on solid fuel burning, phasing out outdated and inefficient heating systems. Provide financial assistance and technical support to households for transitioning to cleaner heating alternatives, such as natural gas, biomass boilers, or heat pumps. Launch public awareness campaigns to educate citizens about the health risks associated with solid fuel burning and the benefits of cleaner heating options.

- **Strengthen air quality monitoring and enforcement**: Expand and modernize the national air quality monitoring network, deploying more sensors in urban areas and near industrial facilities. Make real-time air quality data publicly available through user-friendly platforms and mobile applications. Strengthen enforcement mechanisms to ensure compliance with emission standards, imposing penalties for violations.
- **Foster research and innovation**: Support research and development of cleaner technologies for energy production, transport, and industry. Promote collaboration between research institutions, businesses, and municipalities to translate scientific knowledge into practical solutions. Create incentives for the adoption and deployment of innovative air quality solutions.
- **Engage citizens and build trust**: Launch comprehensive public awareness campaigns to inform citizens about the health impacts of air pollution and the benefits of collective action. Establish platforms for citizen participation in decision-making processes related to air quality management. Ensure transparent communication from authorities about air quality data, policy decisions, and enforcement actions.

Conclusion

Tackling air pollution in Bulgaria demands concerted efforts across various sectors and levels of governance. By identifying the key sources and pollutants, engaging diverse stakeholders, and fostering collaboration between public and private sectors, the country can make meaningful strides toward cleaner air. While challenges remain, adaptive management and transparent communication are essential for the long-term success of air quality improvement initiatives. Through strategic actions such as transitioning to renewable energy, modernizing transportation, and addressing domestic heating emissions, Bulgaria can create a healthier environment for its citizens and set a strong example for other countries facing similar challenges.

5. Conclusion

This report has looked closely at the problem of air pollution in Bulgaria. We used the Wicked Problem Matrix to help us understand this problem. We looked at how complex it is, how uncertain it is, the conflicts it causes, and how big the problem is. This helped us see the many things that cause air pollution in Bulgaria.

Air pollution in Bulgaria is not a simple problem. It is complex because many things are connected to it, like the weather, where the pollution comes from, and the economy. It is hard to know what will happen in the future and how different actions will affect the problem. Also, the report showed that there are conflicts about this problem. People agree that clean air is important, but they have different ideas about how to solve the problem. It is hard for people to work together because they don't have the same power and they don't always talk to each other well. People also don't always trust the government. Air pollution affects the whole country. It has been a problem for a long time and has bad effects on people's health and the environment. Some of these bad effects might not be able to be reversed. But the report shows that if people work together, things can get better.

The report gives ideas about how to make things better. These ideas include using more renewable energy, making transportation better, and checking air quality more often. It is important to remember that solving air pollution is a long process. We need to keep learning and talking to each other to make sure that everyone has clean air. Finally, this report shows that everyone needs to work together to solve the problem of air pollution in Bulgaria. If we understand the problem and work together, we can make Bulgaria a place with cleaner air for everyone.

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Co-funded by the European Union

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2021-1-MK01-KA220-HED-000030188

EXPERIMENTATION REPORT

Mapping Czech Republic's Air Pollution on Wicked Problem Matrix

1. Introduction

Air pollution represents a significant environmental challenge in Czech republic, characterized by its complexity and widespread impacts on human health, ecosystems, and economic activities. This report seeks to analyze the intricate nature of air pollution within the framework of the Wicked Problem Matrix. By evaluating the variables influencing air pollution, their interdependencies, and the non-linear cause-and-effect relationships, this report provides a comprehensive understanding of the issue's multidimensionality.

Drawing on data from a range of sources, the analysis addresses key factors such as emissions from various sectors, meteorological conditions, socioeconomic drivers, and the effectiveness of policy measures. Furthermore, it highlights the regional and national scale of the problem, emphasizing the long-term implications and the need for collaborative, adaptive, and transparent approaches to mitigation.

2. Dimensions of wicked problems

2.1. Complexity

Air pollution in Greece exemplifies a high-complexity problem, characterized by a multitude of variables and significant interdependencies between them. According to the Wicked Problem Matrix framework, the complexity of a problem is determined by the number of influencing factors, their interrelationships, the linearity of cause-and-effect relationships, and the degree of ambiguity in understanding the issue.

This section focuses on the variables that make air pollution a highly complex challenge. The factors include diverse emissions sources, meteorological conditions, geographic and climatic influences, population density, socioeconomic factors, and the role of policies and regulations. Each of these elements interacts dynamically, contributing to a non-linear cause-and-effect relationship and making the issue difficult to fully grasp at a practical level. Additionally, the interplay between emissions and meteorological conditions, as well as the socio-political context, highlights the significant interdependencies inherent in this problem.

By evaluating these variables within the framework of complexity, this analysis seeks to provide a deeper understanding of the intricate dynamics at play in addressing air pollution in Greece.

2.1.1. Variables influencing the problem

The number of variables influencing the air pollution problem in the Czech Republic is high. The sources discuss a variety of factors, including:

- **Inadequate household heating**: Many households rely on outdated and inefficient heating systems, often burning solid fuels like coal, which contribute significantly to particulate matter (PM) emissions (CENIA, 2015).
- **Industrial emissions**: The Czech Republic has a history of heavy industry, and emissions from power plants, ironworks, and other industrial facilities remain a significant source of air pollution (Rakovský, 2016; Juřík & Braathen, 2021).
- **Transboundary pollution**: Air pollution does not respect national borders. The sources acknowledge that emissions from neighboring countries can contribute to poor air quality in the Czech Republic, particularly with regard to PM and ozone (Šauer, Kreuz, & Lisa, 2014; United Nations Economic Commission for Europe, 2013).
- **Natural sources**: While human activity is the primary driver of air pollution, natural sources such as volcanic activity, dust storms, and wildfires can also contribute to the problem, particularly PM (CENIA, 2015).

The interdependencies between these variables are also high. For example, the sources note:

- **The impact of household emissions on total air pollution** is influenced by geography. In areas with higher population density or specific topographical features that trap pollutants, the contribution of household heating to overall air quality can be even more pronounced (State Environmental Fund of the Czech Republic, 2020; Juřík & Braathen, 2021).
- **The effectiveness of emissions fees for stationary sources** depends on the level of stringency of best available technologies (BAT). If BAT standards are not stringent enough, emissions fees may not provide a sufficient incentive for companies to invest in pollution control measures (Juřík & Braathen, 2021).
- **The conversion of emissions into exposure** is dependent on time and space-specific factors, such as weather conditions. For example, stagnant air masses and temperature inversions can exacerbate the concentration of pollutants near the ground level, leading to higher exposure levels for the population (CENIA, 2015).

The air pollution problem can be understood at an abstract, conceptual level (medium). While the problem itself is observable (e.g., smog, poor air quality readings), understanding its causes, impacts, and potential solutions requires conceptual knowledge of factors like:

- **The interaction between human activities and natural systems**: Understanding air pollution requires knowledge of the chemical and physical processes that govern the emission, transport, transformation, and deposition of pollutants in the atmosphere (CENIA, 2015). It also involves understanding how these pollutants interact with ecosystems, human health, and the built environment (State Environmental Fund of the Czech Republic, 2020).
- **Economic and political considerations**: Addressing air pollution involves making choices about resource allocation, technology development, and policy interventions. Understanding the costs and benefits of different mitigation strategies, the role of market mechanisms, and the political feasibility of different policy options is crucial (Rakovský, 2016).

The cause-and-effect relationship of the problem is highly non-linear, and the cause-and-effect relationship is difficult to understand (high). This is due to:

- **The complexity of the interactions between different pollutants and sources**: Pollutants can react with each other in the atmosphere to form secondary pollutants, such as ozone and secondary PM, which can have different health and environmental impacts than the original pollutants (Šauer, Kreuz, & Lisa, 2014; CENIA, 2015). Additionally, the relative contributions of different sources can vary significantly depending on location, time of year, and other factors (Juřík & Braathen, 2021).
- **The delayed and long-term effects of some pollutants**: Some pollutants, such as heavy metals and persistent organic pollutants, can accumulate in the environment and have long-lasting health and ecological impacts (United Nations Economic Commission for Europe, 2013). This makes it difficult to establish direct causal links between emissions and their effects, as the consequences may only become apparent years or even decades later (CENIA, 2015).
- **The difficulty in measuring the true costs of pollution and the effectiveness of different mitigation measures**: The economic and social costs of air pollution, including health care expenses, lost productivity, and damage to ecosystems, are difficult to quantify accurately (Rakovský, 2016). Moreover, the effectiveness of different mitigation measures can be influenced by a variety of factors, making it challenging to assess their true impact (State Environmental Fund of the Czech Republic, 2020).

The air pollution problem is highly ambiguous and difficult to understand due to a lack of information or conflicting information (high). Sources highlight:

- **Uncertainties regarding the dominant source of pollution**: While household heating is recognized as a major contributor, the sources note the need for more precise data on the shares of different sources to effectively target mitigation efforts (Šauer, Kreuz, & Lisa, 2014; State Environmental Fund of the Czech Republic, 2020). For example, the exact proportion of household pollution in total air pollution in a given locality is often uncertain (State Environmental Fund of the Czech Republic, 2020).
- **A lack of comprehensive data on the real shares of particular pollution sources**: This data gap hinders the development of targeted and effective air quality management plans (Šauer, Kreuz, & Lisa, 2014). The sources advocate for more robust monitoring and data collection efforts to improve understanding of the problem (State Environmental Fund of the Czech Republic, 2020; Juřík & Braathen, 2021).
- **A large number of contaminated sites with unknown risks** (Czech Ministry of the Environment, 2020). These sites may pose a threat to air quality if they release pollutants into the atmosphere, adding another layer of complexity to the problem.

Conclusion

The problem's complexity, non-linear cause-and-effect relationships, and ambiguity highlight the need for further research, data collection, and multi-faceted solutions. Addressing air pollution in the Czech Republic will require an integrated approach that considers both local and transboundary sources, utilizes a combination of policy instruments, and prioritizes community engagement and awareness-raising.

2.2. Uncertainty

Uncertainty is a defining characteristic of wicked problems, reflecting the lack of knowledge, stability, and predictability surrounding both the problem and its potential solutions. In the context of air pollution in Greece, uncertainty arises from challenges in accurately predicting the problem, the rapidity of its changes, the ambiguity in understanding its causes and effects, and the significant risks associated with its negative outcomes.

Air pollution in the Czech Republic is a complex and evolving issue that poses significant risks to both human health and the environment. The predictability of the problem is moderate, as various interconnected factors, such as meteorological conditions, industrial emissions, and household heating practices, make it challenging to accurately forecast pollution levels and their specific impacts. The problem is also characterized by a moderate

rate of change, with some improvements observed due to policy measures and technological advancements, though challenges persist. Despite efforts to mitigate pollution, the issue remains highly relevant due to its substantial health and ecological impacts. The level of ambiguity surrounding the problem is medium, requiring further research to understand the precise contributions of different pollution sources and the formation of secondary pollutants. Overall, the risks associated with air pollution in the Czech Republic are high, underscoring the urgent need for continued action and intervention to address its widespread consequences.

Predictability of the problem

Medium: Air pollution in the Czech Republic exhibits a moderate level of predictability. While the general problem is recognized, precisely forecasting its severity and specific impacts can be difficult.

Contributing factors: Multiple interconnected factors influence air quality, making accurate predictions challenging (State Environmental Fund of the Czech Republic, 2020).

- **Meteorological conditions**: Wind patterns, temperature inversions, and precipitation levels significantly influence pollutant dispersion and concentration. These weather patterns can be variable and unpredictable, impacting the severity of air pollution episodes (Rakovský, 2016; Juřík & Braathen, 2021).
- **Industrial emissions**: The Czech Republic has a history of heavy industry, which continues to contribute to air pollution. Fluctuations in industrial production and the adoption of emission control technologies can influence pollution levels, adding to the difficulty of prediction (Juřík & Braathen, 2021; State Environmental Fund of the Czech Republic, 2020).
- **Household heating practices**: Solid fuel burning for residential heating, particularly in older buildings, remains a significant source of particulate matter and other pollutants, especially during the colder months (State Environmental Fund of the Czech Republic, 2020; Šauer, Kreuz, & Lisa, 2014). Variations in heating practices and fuel types used across households further complicate predictability.

Rate of change

Medium: The air pollution problem in the Czech Republic is characterized by a moderate rate of change. While improvements have been observed, primarily due to policy measures and technological progress, challenges remain.

- **Policy interventions**: The Czech Republic has implemented various policies to address air pollution, including emission limits for industrial facilities, air quality

standards, and programs to promote cleaner heating solutions (Šauer, Kreuz, & Lisa, 2014; Juřík & Braathen, 2021). These efforts have contributed to a gradual reduction in certain pollutants.

- **Technological advancements**: The adoption of cleaner technologies in industry and transportation, such as improved emission control systems and the promotion of electric vehicles, has played a role in mitigating air pollution (Rakovský, 2016; United Nations Economic Commission for Europe, 2013).
- **Persistent challenges**: Despite these positive developments, air pollution remains a concern, especially in industrial areas and during periods of unfavorable weather conditions. Certain pollutants, such as particulate matter, continue to exceed recommended levels in some regions (State Environmental Fund of the Czech Republic, 2020; CENIA, 2015).

Ambiguity and difficulty to understand

Medium: Air pollution in the Czech Republic presents a moderate level of ambiguity, demanding further research to fully grasp the intricate interplay of contributing factors.

- **Understanding primary and secondary pollutants**: While monitoring and analysis of primary pollutants emitted directly from sources are relatively well-established, understanding the formation and behavior of secondary pollutants poses a greater challenge (CENIA, 2015; Šauer, Kreuz, & Lisa, 2014). These secondary pollutants, such as ozone and fine particulate matter, are formed through complex chemical reactions involving primary pollutants and atmospheric conditions.
- **Source apportionment**: Determining the precise contribution of various sources to overall air pollution levels remains an area requiring further research. Accurately quantifying the share of industrial emissions, transportation, household heating, and other sources is crucial for targeted interventions (CENIA, 2015).

Level of risk for negative outcomes

High: The potential negative outcomes of air pollution in the Czech Republic are substantial, posing a high level of risk to human health and the environment (CENIA, 2015).

- **Human health impacts**: Exposure to air pollutants is linked to a range of adverse health effects, including:
    - **Respiratory problems**: Fine particulate matter can penetrate deep into the lungs, exacerbating asthma, bronchitis, and other respiratory diseases (CENIA, 2015; Šauer, Kreuz, & Lisa, 2014).

  - **Cardiovascular disease**: Air pollution is associated with an increased risk of heart attacks, strokes, and other cardiovascular issues (Rakovský, 2016; Juřík & Braathen, 2021).
  - **Cancer**: Certain air pollutants are classified as carcinogens, contributing to an elevated risk of lung cancer and other types of cancer (State Environmental Fund of the Czech Republic, 2020; CENIA, 2015).
- **Ecological impacts**: Air pollution has far-reaching consequences for ecosystems:
  - **Acidification**: Sulfur dioxide and nitrogen oxides emitted into the atmosphere contribute to acid rain, damaging forests, lakes, and other sensitive ecosystems (CENIA, 2015).
  - **Eutrophication**: Nitrogen compounds from air pollution can deposit on water bodies, leading to excessive nutrient levels and disrupting aquatic ecosystems (Šauer, Kreuz, & Lisa, 2014).
  - **Damage to vegetation**: Ozone and particulate matter can impair plant growth and reduce crop yields, impacting agricultural productivity (CENIA, 2015; Juřík & Braathen, 2021).

In conclusion, air pollution in the Czech Republic constitutes a wicked problem with moderate predictability and a moderate rate of change. The complexity of the problem demands a deeper understanding of the interplay between various sources, pollutants, and atmospheric conditions. However, the potential consequences for human health and ecosystems are significant, highlighting the high level of risk associated with this issue. The urgency of addressing air pollution is underscored by the substantial health burdens and environmental damage it can cause.

2.3. Conflict

Conflict is a central characteristic of wicked problems, arising from the competing interests, values, and priorities of diverse stakeholders. In the context of air pollution, the complexity is heightened by the challenge of reconciling these conflicting perspectives to develop effective and equitable solutions.

This section explores the dimensions of conflict in air pollution management, focusing on the number of stakeholders affected, the alignment of their interests and values, the balance of power, the quality of communication, and the level of trust among them. With a large and diverse group of stakeholders, including governments, industries, communities, and environmental organizations, the interests and values often diverge, creating misalignments and imbalances that complicate decision-making. Additionally, communication and trust, key elements for effective collaboration, can range from limited to poor, further exacerbating the challenges.

By analyzing these aspects of stakeholder dynamics, this section aims to shed light on the sources of conflict and their implications for air quality management strategies, highlighting the need for inclusive, transparent, and trust-building approaches to foster collaboration and achieve sustainable solutions.

The sources provided focus mainly on technical and policy aspects of air pollution mitigation in the Czech Republic. They do not contain substantial information about the perspectives and interests of various stakeholders affected by air pollution. Therefore, a comprehensive answer to your question, solely based on the provided sources, is not possible.

However, the sources do offer some insights:

Number of stakeholders affected

High: While not explicitly stated, the sources suggest a large number of stakeholders are involved in the air pollution issue in the Czech Republic. This can be inferred from:

- Government agencies at various levels are involved in developing and implementing air quality improvement programs, including the Ministry of the Environment and the Czech Hydrometeorological Institute (State Environmental Fund of the Czech Republic, 2020; Juřík & Braathen, 2021).
- Industries, particularly manufacturing and energy sectors, are significant sources of air pollution and subject to regulations like emission limits and air pollution taxes (Juřík & Braathen, 2021).
- The public is implicitly affected by air pollution, as the sources mention the goal of protecting human health and improving air quality in populated areas (CENIA, 2015).
- Neighboring countries are also impacted by transboundary air pollution, requiring international cooperation for effective solutions (United Nations Economic Commission for Europe, 2013).

Alignment of stakeholder interests and values

Misaligned/partially aligned: The sources allude to potential conflicts and differing priorities among stakeholders:

- **Economic competitiveness vs. environmental protection**: The analysis of the air pollution tax suggests that while it aims to reduce emissions, its rates do not adequately reflect environmental and social damage costs, potentially favoring economic interests over environmental protection (Juřík & Braathen, 2021).

- **Implementation costs and timelines**: The discussion of emission limits highlights that companies have adapted to stricter limits, but the extent to which these limits drive emission reductions remains unclear. This suggests potential conflict between regulatory goals and industry preferences for gradual implementation (Juřík & Braathen, 2021).
- **Information Asymmetry**: The sources mention that there is limited literature comparing different mitigation measures and acknowledge information asymmetry between firms and the government regarding the costs of implementing environmentally friendly technologies (Šauer, Kreuz, & Lisa, 2014). This lack of transparency and shared understanding could fuel conflicts.

Balance of stakeholder power, communication, and trust

- The sources do not offer enough information to assess the balance of power, the effectiveness of communication, or the level of trust between stakeholders.

Overall, while the sources provide a limited perspective on stakeholder dynamics, they suggest that the air pollution issue in the Czech Republic involves various stakeholders with potentially misaligned interests and values. This complexity likely contributes to the challenges of implementing effective air quality improvement measures.

2.4. Scale

The scale of a wicked problem reflects the extent of its spatial, temporal, and societal impact. Understanding the scale is crucial for evaluating the breadth and depth of a problem's effects, including the geographic areas it influences, the duration of its consequences, and the severity of its impacts on individuals, organizations, and ecosystems.

This section examines the scale of air pollution in the Czech Republic, assessing its geographic reach from international to local levels. It explores the various spatial dimensions, highlighting the transboundary nature of the issue, as well as national, regional, and local variations in pollution levels and sources. Additionally, the analysis covers the temporal aspects of air pollution, emphasizing its long-term persistence, the medium-term effects of implemented policies, and the short-term influences of weather and traffic patterns. The significant impacts on human health, ecosystems, and the economy are discussed, along with the large number of individuals and organizations affected. Finally, the reversibility of air pollution is considered, identifying both mitigable aspects and irreversible damages that require continued efforts to address.

Based on the provided sources, the scale of the air pollution problem in the Czech Republic can be characterized as follows:

Spatial scale:

- **International**: Air pollution is inherently a transboundary issue, and the sources acknowledge this by referencing international agreements and collaborations like the Convention on Long-range Transboundary Air Pollution (CLRTAP) and the European Union's National Emission Ceilings Directive (NECD) (European Environment Agency, 2014; United Nations Economic Commission for Europe, 2013).
- **National**: The sources primarily focus on air pollution within the Czech Republic, analyzing national policies, emission trends, and health impacts (CENIA, 2015; Šauer, Kreuz, & Lisa, 2014; Juřík & Braathen, 2021).
- **Regional**: The sources mention specific regions within the Czech Republic that face higher pollution levels or have unique challenges (Šauer, Kreuz, & Lisa, 2014; CENIA, 2015).
- **Local**: The sources highlight that air quality varies significantly within localities and is influenced by factors like population density, industrial activity, and traffic patterns (Czech Republic, 2018; State Environmental Fund of the Czech Republic, 2020).

Temporal scale:

- **Long-term**: The sources analyze historical emission trends dating back to 1990, indicating the persistent and long-term nature of the air pollution problem (United Nations Economic Commission for Europe, 2013; CENIA, 2015). They also set targets for emission reductions and air quality improvement extending to 2030 and beyond (State Environmental Fund of the Czech Republic, 2020; Ministry of the Environment of the Czech Republic, 2021).
- **Medium-term**: The sources assess the effectiveness of policies and measures implemented over the past decade and discuss their impacts on air quality trends (CENIA, 2015; Juřík & Braathen, 2021; State Environmental Fund of the Czech Republic, 2020).
- **Short-term**: The sources acknowledge the influence of short-term factors like weather patterns and daily traffic fluctuations on air pollution levels (Juřík & Braathen, 2021; CENIA, 2015).

Impact Level:

High: The sources consistently emphasize the significant negative impacts of air pollution on:

- **Human health**: Highlighting respiratory problems, cardiovascular diseases, and increased mortality rates (Šauer, Kreuz, & Lisa, 2014; Juřík & Braathen, 2021; CENIA, 2015).
- **Ecosystems**: Discussing acidification, eutrophication, and damage to vegetation (Šauer, Kreuz, & Lisa, 2014; CENIA, 2015; United Nations Economic Commission for Europe, 2013).
- **Economic costs**: Referencing healthcare expenses, lost productivity, and damage to infrastructure (Juřík & Braathen, 2021; Ministry of the Environment of the Czech Republic, 2021).

Number Affected:

High: The sources imply a large number of people and organizations affected by air pollution:

- **General population**: The sources highlight concerns for public health and the need to improve air quality in populated areas (State Environmental Fund of the Czech Republic, 2020; Šauer, Kreuz, & Lisa, 2014).
- **Industries**: Various sectors, particularly those contributing to emissions, are subject to regulations and economic impacts (Šauer, Kreuz, & Lisa, 2014; Juřík & Braathen, 2021; United Nations Economic Commission for Europe, 2013).
- **Government agencies**: Multiple agencies are involved in managing and mitigating air pollution, requiring coordination and resources (European Environment Agency, 2014; CENIA, 2015; Ministry of the Environment of the Czech Republic, 2021).

Reversibility:

Partly Reversible: While some aspects of air pollution can be mitigated through emission reductions and technological advancements, the sources suggest:

- **Persistent challenges**: The long-term nature of the problem and the complexity of stakeholder dynamics indicate that achieving significant and lasting improvements will be challenging (CENIA, 2015; Juřík & Braathen, 2021).
- **Irreversible damage**: The sources acknowledge that air pollution has already caused substantial damage to ecosystems and human health, some of which may be irreversible (Šauer, Kreuz, & Lisa, 2014; Ministry of the Environment of the Czech Republic, 2021).

In summary, the air pollution problem in the Czech Republic is a wicked problem with international, national, regional, and local dimensions. Its impacts are high, affecting a large number of people and organizations over long, medium, and short timescales. While some aspects of the problem are partly reversible, achieving substantial and lasting improvements requires sustained effort and collaboration among diverse stakeholders.

3. Strategies

Addressing wicked problems requires a structured approach that connects real-world strategies to established frameworks for problem-solving. The wicked problems matrix provides a set of strategies—breaking the problem down, identifying stakeholders, fostering collaboration, prototyping solutions, adopting adaptive management, and ensuring transparency—that can be used to tackle complex and interconnected challenges.

This section aims to analyze the strategies and actions discussed in the provided sources and map them to the wicked problems matrix framework. By aligning real-world approaches with structured strategies, the section provides insights into how existing efforts can be strengthened to more effectively address the multifaceted issue of air pollution in the Czech Republic. This mapping process helps evaluate the success of current measures, identify gaps in addressing key factors such as emission sources, stakeholder involvement, and collaboration, and suggests potential improvements for sustainable and adaptive problem-solving. The goal is to enhance the effectiveness of ongoing actions and ensure a more comprehensive approach to tackling air pollution.

The sources offer various strategies and actions to tackle air pollution in the Czech Republic. These can be mapped to the provided strategies for solving wicked problems:

3.1. Analysis of strategies and actions:

- **Breaking down the problem**: The sources consistently differentiate between various pollutants, emission sources, and affected areas (urban, rural, specific regions). This targeted approach helps address specific aspects of the complex air pollution problem.
    - Sources (Czech Hydrometeorological Institute, 2022; Šauer, Kreuz, & Lisa, 2014) illustrate breaking down the problem by focusing on specific pollutants like PM10, PM2.5, benzo[a]pyrene, and ground-level ozone, analyzing their individual sources and trends.
    - Sources (State Environmental Fund of the Czech Republic, 2020; Šauer, Kreuz, & Lisa, 2014) demonstrate targeting specific geographical areas with initiatives like monitoring air pollution in “white areas” (areas lacking

sufficient monitoring) and developing action plans tailored to local pollution sources.

- **Identifying stakeholders**: The sources implicitly acknowledge various stakeholders involved:
  - Government agencies at different levels (national, regional, local) responsible for developing and enforcing regulations, implementing monitoring programs, and allocating funding for air quality improvement initiatives.
  - Industries as significant emission sources, particularly the energy and manufacturing sectors, subject to regulations and incentives.
  - The public as those affected by air pollution's health and environmental impacts.
  - Neighboring countries impacted by transboundary air pollution.
- **Collaboration**: The sources highlight the importance of collaboration:
  - **International cooperation** is crucial for addressing transboundary air pollution, as exemplified by the Czech Republic's participation in the Convention on Long-range Transboundary Air Pollution (CLRTAP) (United Nations Economic Commission for Europe, 2013; CENIA, 2015).
  - **National and local collaboration** is also emphasized, with sources mentioning the involvement of various ministries, municipalities, and regional authorities in developing and implementing air quality improvement programs (Šauer, Kreuz, & Lisa, 2014; State Environmental Fund of the Czech Republic, 2020).
- **Prototyping solutions**: The sources provide examples of implemented and proposed solutions, essentially acting as prototypes to assess effectiveness:
  - **Emission limits and air pollution taxes**: These economic instruments aim to incentivize emission reductions (Rakovský, 2016; Juřík & Braathen, 2021).
  - **Best available technologies (BAT)**: Promoting the adoption of cleaner technologies in various industries (CENIA, 2015).
  - **Energy efficiency improvements and fuel switching**: Encouraging the use of renewable energy sources and reducing reliance on fossil fuels (CENIA, 2015; Juřík & Braathen, 2021).
  - **Monitoring and data analysis**: Collecting data to understand pollution sources and trends to inform targeted interventions (State Environmental Fund of the Czech Republic, 2020; CENIA, 2015).
- **Adaptive management**: The sources suggest a willingness to adapt and improve policies and strategies based on monitoring and evaluation:
  - The revision of the air pollution tax system and the ongoing evaluation of its effectiveness exemplify this adaptive approach (Rakovský, 2016; Juřík & Braathen, 2021).

  - The emphasis on research and development, along with the recognition of information gaps, further supports the need for continuous learning and adaptation (United Nations Economic Commission for Europe, 2013; CENIA, 2015).
- **Transparency**: While the sources do not explicitly discuss transparency, they emphasize the importance of public awareness and access to information about air quality:
  - The development of action plans and the dissemination of information on air pollution's health impacts suggest efforts towards transparency (State Environmental Fund of the Czech Republic, 2020; United Nations Economic Commission for Europe, 2013).
  - Promoting public participation in decision-making processes can further enhance transparency and accountability (CENIA, 2015).

3.2. Proposed strategies and activities:

Based on the analysis above and the provided framework for solving wicked problems, these strategies and activities can help address air pollution in the Czech Republic:

- **Further breakdown**: Conduct in-depth analyses of specific emission sources within key industries to pinpoint areas for targeted interventions.
- **Stakeholder mapping**: Systematically map all stakeholders, their interests, and their influence to facilitate communication and identify potential conflicts and opportunities for collaboration.
- **Collaborative platforms**: Establish formal platforms for ongoing dialogue and collaboration between government agencies, industry representatives, scientific experts, and public interest groups.
- **Pilot projects**: Implement pilot projects testing innovative technologies and approaches for emission reduction and air quality improvement, allowing for evaluation and adaptation.
- **Monitoring and evaluation framework**: Develop a comprehensive monitoring and evaluation framework to assess the effectiveness of implemented measures and inform adaptive management strategies.
- **Transparency and communication**: Enhance transparency by making data on air quality, emission sources, and policy decisions readily accessible to the public. Implement targeted communication campaigns to raise awareness about air pollution's health and environmental impacts and promote individual and collective action.

By strategically applying the framework for solving wicked problems, the Czech Republic can continue to make progress in tackling the complex challenge of air pollution.

4. Conclusion

In conclusion, addressing air pollution in the Czech Republic requires a comprehensive and strategic approach due to the complex, interconnected nature of the problem. The analysis of current strategies reveals the importance of breaking down the issue into manageable components, identifying relevant stakeholders, and fostering collaboration across various levels—national, regional, and international. As highlighted in the report, air pollution is a multi-faceted problem with diverse sources ranging from industrial emissions to household heating practices, meteorological conditions, and even transboundary pollution from neighboring countries. This complexity demands targeted interventions tailored to specific regions and pollutants, as well as clear communication between all involved parties.

The Czech Republic has already made strides in addressing air pollution through policy measures, technological advancements, and international cooperation. Policies such as emission limits, air pollution taxes, and investments in cleaner technologies have contributed to some improvements in air quality. However, challenges remain, particularly in areas where pollution levels continue to exceed health and environmental standards, or where the effects of long-term exposure to pollutants become apparent only after years. Therefore, it is crucial to build upon existing actions by integrating adaptive management practices that allow for ongoing monitoring, evaluation, and adjustment of strategies.

The proposed strategies outlined in this report, including targeted stakeholder mapping, pilot projects for testing innovative technologies, and the development of a comprehensive monitoring and evaluation framework, are essential steps in refining current practices. In particular, establishing formal platforms for collaboration among government agencies, industries, scientific experts, and public interest groups will enable better coordination and decision-making. Moreover, enhancing transparency in air quality data, improving public awareness of health and environmental impacts, and promoting community engagement will empower citizens to take part in the decision-making process, which is vital for achieving lasting solutions.

By strategically applying the framework for solving wicked problems, the Czech Republic can continue to make progress in tackling the complex challenge of air pollution. Through sustained and collaborative efforts, the nation can develop more sustainable and effective solutions that not only improve air quality but also protect public health, ecosystems, and economic stability. It will require continued research, innovation, and cooperation, as well as a commitment to long-term, systemic change. The path to cleaner air is challenging, but with coordinated action and adaptive strategies, significant improvements are possible.

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2. Dimensions of wicked problems

2.1. Complexity

Air pollution in Greece exemplifies a high-complexity problem, characterized by a multitude of variables and significant interdependencies between them. According to the Wicked Problem Matrix framework, the complexity of a problem is determined by the number of influencing factors, their interrelationships, the linearity of cause-and-effect relationships, and the degree of ambiguity in understanding the issue.

This section focuses on the variables that make air pollution a highly complex challenge. The factors include diverse emissions sources, meteorological conditions, geographic and climatic influences, population density, socioeconomic factors, and the role of policies and regulations. Each of these elements interacts dynamically, contributing to a non-linear cause-and-effect

relationship and making the issue difficult to fully grasp at a practical level. Additionally, the interplay between emissions and meteorological conditions, as well as the socio-political context, highlights the significant interdependencies inherent in this problem.

By evaluating these variables within the framework of complexity, this analysis seeks to provide a deeper understanding of the intricate dynamics at play in addressing air pollution in Greece.

2.1.1. Variables influencing the problem

High: The problem of air pollution is influenced by a large number of variables (IQAir, 2023; Fraport Greece, 2020; NCESD, 2019). These variables include:

- **Emissions sources:** These vary significantly and include industrial activities, transportation, residential heating (especially using biomass), agriculture, and even transborder pollution (NCESD, 2019; Fameli, 2014; European Environment Agency, 2014; NCESD, 2018). Each source has a different composition of pollutants emitted.
- **Meteorological factors:** Wind speed, temperature inversions, boundary layer depth, and solar irradiance all play a crucial role in pollutant accumulation, dispersion, and chemical transformations (Anastasaki et al., 2021).
- **Geographic and climatic conditions:** The location, topography, and regional climate patterns can influence pollutant transport and concentration levels (NCESD, 2019; NCESD, 2018).
- **Population density and urbanization:** Higher population density and urban sprawl lead to increased emissions from transportation and residential heating, particularly in areas like Athens and Thessaloniki (NCESD, 2018; Anastasaki et al., 2021).
- **Socioeconomic factors:** Economic recession and energy poverty can drive the use of cheaper but more polluting fuels like biomass (HRDC, 2020; UNECE, 2018). Access to clean energy alternatives and resources to invest in pollution mitigation measures also vary across populations (Progiou et al., 2023; OECD, 2020).
- **Policy and regulations:** The effectiveness of policies, implementation of regulations such as the National Air Pollution Control Programme (NAPCP), and international agreements like the Geneva Convention on Long Range Transboundary Air Pollution have a significant impact (UNECE, 2018; Hellenic Statistical Authority, 2021; WHO, 2024).

2.1.2. Interdependencies between variables

High: There is a high degree of interdependency between the variables influencing air pollution (Fraport Greece, 2020; NCESD, 2019). For example:

- **Emissions and meteorology:** Wind patterns and atmospheric stability can significantly impact the dispersion or concentration of pollutants emitted from various sources (Anastasaki et al., 2021).
- **Climate change impacts:** Climate change can exacerbate air pollution by altering weather patterns and increasing the frequency of extreme events like heatwaves, which influence ozone formation and particulate matter concentration (IQAir, 2023).
- **Policy and socioeconomic factors:** Policies aimed at reducing emissions from certain sectors, such as promoting the adoption of renewable energy or electric vehicles, can be influenced by economic conditions, public acceptance, and the affordability of cleaner technologies (UNECE, 2018).
- **Transboundary pollution:** Air pollution doesn't respect geographical boundaries. Emissions from neighboring countries can contribute to pollution levels in Greece, and vice versa (MDAT, 2021).

2.1.3. Level of understanding the problem

Medium: The problem of air pollution can be understood at an abstract, conceptual level (IQAir, 2023; European Environment Agency, 2014). While the basic science of air pollution is well established, the complexity arises from the intricate interactions between various sources, meteorological conditions, and geographical factors. Research and modeling efforts are continually being undertaken to better understand these interrelationships and predict the impacts of specific measures.

2.1.4. Linearity of cause-and-effect relationship

High: The cause-and-effect relationship in air pollution is highly non-linear (Anastasaki et al., 2021; Koukouli et al., 2021). The impact of a specific emission source on air quality isn't directly proportional and is significantly modified by meteorological conditions, atmospheric chemistry, and the presence of other pollutants. For example:

- **Non-linear response to emission reductions:** A 15% reduction in all precursor emissions may not result in a 15% reduction in PM2.5 concentrations due to complex chemical interactions in the atmosphere (MDAT, 2021).

- **Meteorological variability:** The same amount of emissions released under different weather conditions can lead to drastically different air quality outcomes (Anastasaki et al., 2021).
- **Feedback loops:** Air pollution can impact climate change, which in turn can influence weather patterns and further affect air quality, creating feedback loops (IQAir, 2023).

2.1.5. Ambiguity and difficulty in understanding the problem

Medium: While air pollution is a well-defined problem with considerable research and data available, ambiguity arises from the complexity of interactions and the difficulty in predicting the exact impact of specific measures (Koukouli et al., 2021). For instance:

- **Uncertainty in emission inventories:** There are inherent uncertainties in estimating emissions from various sources, especially those that are diffuse or not well-monitored (Koukouli et al., 2021).
- **Limitations of modeling:** While atmospheric models have advanced significantly, they are still limited by computational power, data availability, and the ability to fully capture the complexities of atmospheric processes (Anastasaki et al., 2021).
- **Conflicting information:** There can be conflicting information about the effectiveness of certain mitigation measures or the relative contribution of different sources to overall pollution levels (UNECE, 2018).

Conclusion

Based on the above, it can be concluded that the complexity of air pollution in Greece stems from a multitude of variables, their intricate interdependencies, and highly non-linear cause-and-effect relationships. Addressing this issue requires a comprehensive and multi-dimensional approach that reflects the scientific, socioeconomic, and policy-specific factors unique to the Greek context.

2.2. Uncertainty

Uncertainty is a defining characteristic of wicked problems, reflecting the lack of knowledge, stability, and predictability surrounding both the problem and its potential solutions. In the context of air pollution in Greece, uncertainty arises from challenges in accurately predicting the problem, the rapidity of its changes, the ambiguity in understanding its causes and effects, and the significant risks associated with its negative outcomes.

This section explores these dimensions of uncertainty, evaluating the predictability of air pollution using models and data, the variability of pollution levels over time, and the inherent complexity and ambiguity in understanding the issue. Additionally, it examines the substantial risks posed by air pollution to human health, ecosystems, and economic stability. By addressing these factors, the analysis aims to provide a comprehensive understanding of the uncertainties that complicate efforts to mitigate air pollution in Greece.

2.2.1. How difficult is it to predict the problem

Medium. Air pollution can be predicted with some degree of accuracy using models and data analysis (IQAir, 2023; Fraport Greece, 2020; NCESD, 2019), which allow us to understand the impact of emissions and meteorological conditions on air quality levels. However, various factors can significantly influence air pollution, making it challenging to predict with absolute certainty (European Environment Agency, 2014). These factors include:

- **Emissions from various sources:** including vehicles, industries, power plants, residential heating, and agriculture, which can vary greatly depending on location, time of year, and economic activities (Fameli, 2014; NCESD, 2018).
- **Meteorological conditions:** including wind speed and direction, temperature inversions, and boundary layer depth, which can impact the accumulation and dispersion of pollutants (NCESD, 2019).
- **Transboundary pollution:** air pollution can travel across borders, making it difficult to predict the impact of local emissions on air quality (MDAT, 2021).
- **Unexpected events:** such as wildfires, volcanic eruptions, and dust storms, which can cause sudden spikes in air pollution levels (OECD, 2020).

2.2.2. How rapidly the problem changes over time

Medium to high. Air pollution levels can fluctuate rapidly depending on the combination of factors mentioned above. For instance, in Greece, PM10 levels rise during the winter months due to increased residential heating, particularly biomass burning (IQAir, 2023; HRDC, 2020). Sudden changes in emissions, such as those caused by economic crises or pandemic lockdowns, can also lead to rapid shifts in air quality (Koukouli et al., 2021; Progiou et al., 2023).

2.2.3. How ambiguous and difficult to understand is the problem

Medium to high. While the basic principles of air pollution are well-established, understanding its specific causes and effects in a particular location can be quite complex. The

interaction between different emission sources, meteorological conditions, and atmospheric chemistry creates a complex system that can be difficult to fully grasp (European Environment Agency, 2014). Furthermore, data availability, monitoring limitations, and research gaps can contribute to the ambiguity surrounding air pollution (Hellenic Statistical Authority, 2021). For example, a study in Greece encountered challenges in interpreting air quality data due to limitations in sampling and pollutant parameters selection (Progiou et al., 2023).

2.2.4. What is the level of risk for negative outcomes of the problem

High. Air pollution has well-documented negative impacts on human health, ecosystems, and the economy (Fameli, 2014; WHO, 2024). Exposure to air pollutants, especially PM2.5, has been linked to respiratory and cardiovascular diseases, reduced life expectancy, and increased healthcare costs (Progiou et al., 2023; Koukouli et al., 2021; MDAT, 2021). Air pollution can also damage crops, forests, and aquatic ecosystems, impacting biodiversity and food security. Additionally, it can reduce visibility, impact tourism, and contribute to climate change (Fameli, 2014; OECD, 2020). These significant potential negative outcomes make air pollution a high-risk problem.

It is important to consider the impact of indoor air pollution, which can be a significant contributor to overall air pollution exposure. The FRESH AIR study in Greece highlighted that indoor biomass burning during periods of economic recession can lead to elevated PM2.5 levels exceeding WHO guidelines (Koukouli et al., 2021; HRDC, 2020). This finding underscores the need for addressing both indoor and outdoor sources of air pollution to effectively mitigate health risks, especially in economically vulnerable communities (UNECE, 2018).

Conclusion

The uncertainty surrounding air pollution in Greece underscores the complexity of addressing this wicked problem. While predictive models provide some insights into the problem, factors such as emissions variability, meteorological influences, transboundary pollution, and unexpected events limit the accuracy of predictions. The rapid changes in pollution levels, particularly due to seasonal heating practices or sudden socio-economic shifts, further complicate mitigation efforts.

Understanding air pollution is also hindered by significant ambiguity. The interplay of diverse emission sources, atmospheric conditions, and data limitations creates challenges in fully grasping the issue. Additionally, the high risk of negative outcomes—including severe impacts

on human health, ecosystems, and economic well-being—highlights the urgency of developing effective solutions.

2.3. Conflict

Conflict is a central characteristic of wicked problems, arising from the competing interests, values, and priorities of diverse stakeholders. In the context of air pollution, the complexity is heightened by the challenge of reconciling these conflicting perspectives to develop effective and equitable solutions.

This section explores the dimensions of conflict in air pollution management, focusing on the number of stakeholders affected, the alignment of their interests and values, the balance of power, the quality of communication, and the level of trust among them. With a large and diverse group of stakeholders, including governments, industries, communities, and environmental organizations, the interests and values often diverge, creating misalignments and imbalances that complicate decision-making. Additionally, communication and trust, key elements for effective collaboration, can range from limited to poor, further exacerbating the challenges.

By analyzing these aspects of stakeholder dynamics, this section aims to shed light on the sources of conflict and their implications for air quality management strategies, highlighting the need for inclusive, transparent, and trust-building approaches to foster collaboration and achieve sustainable solutions.

The provided materials primarily address technical aspects of air quality, pollution sources, and mitigation strategies, often focusing on regulatory perspectives. While stakeholders are broadly mentioned, the materials lack detailed exploration of their nuanced interests and perspectives. For example, reports on air quality frequently highlight the role of governments, institutions, and citizens in monitoring air pollution but do not analyze how different groups are affected or their specific interests (IQAir, 2023).

Similarly, other documents discuss environmental and social policies, listing stakeholder groups such as local communities, government authorities, and airport users. However, these discussions do not delve into the unique needs, concerns, or potential conflicts of interest among these groups (Fraport Greece, 2020; NCESD, 2018). Cost-efficient policies for PM10 reduction have also been proposed, yet they focus primarily on stakeholder awareness and support without addressing the differentiated impacts or interests of specific groups (Progiou et al., 2023).

Some documents acknowledge the importance of stakeholder engagement but stop short of specifying their perspectives. For instance, information dissemination is mentioned as a tool to engage stakeholders, but the materials often fail to address their diverse needs or perspectives (NCESD, 2019). National and supranational stakeholders are recognized in policy plans, but the discussions remain centered on reporting actions and emissions rather than analyzing stakeholder dynamics (UNECE, 2018). Additionally, summaries of environmental reports emphasize raising awareness without evaluating the specific roles or conflicts among stakeholders (NCESD, 2018).

Conclusion

This gap in analyzing stakeholder interests and interactions limits the understanding of complexities in implementing air quality policies and their equitable effectiveness. Moving forward, a comprehensive stakeholder analysis could address this gap by identifying key groups, understanding their economic, social, and environmental interests, and assessing their influence and potential for collaboration or conflict. Integrating these insights into policy design and implementation could lead to more inclusive and effective air quality management strategies.

2.4. Scale

The scale of a wicked problem reflects the extent of its spatial, temporal, and societal impact. Understanding the scale is crucial for evaluating the breadth and depth of a problem's effects, including the geographic areas it influences, the duration of its consequences, and the severity of its impacts on individuals, organizations, and ecosystems.

This section examines the scale of air pollution in Greece by assessing its geographic reach, from local and regional effects to its national implications. It also explores the temporal dimensions of air pollution, highlighting its long-term persistence and cumulative impacts. Additionally, the analysis evaluates the problem's high level of impact on health, the environment, and the economy, as well as the large number of people and organizations it affects. Finally, the reversibility of air pollution is considered, identifying aspects that can be mitigated alongside those with lasting effects.

By analyzing these dimensions, this section provides a comprehensive understanding of the scale of air pollution, offering insights into its challenges and the efforts needed for effective management.

2.4.1. What is the area that this problem affects

Air pollution in Greece affects both specific regions and the entire country. While certain regions might experience higher pollution levels due to localized factors, the issue extends nationally through various sources and atmospheric processes. For example, varying PM2.5 levels across Greek cities highlight regional differences, as indicated in reports (IQAir, 2023). However, national policies and strategies are needed to address the broader problem. Additionally, studies emphasize the national and regional impacts of air pollution, including its effects on Thessaloniki and rural Crete (Fameli, 2014; NCESD, 2018).

2.4.2. What is the time length this problem affects

Air pollution is a long-term problem with both acute and chronic impacts. The accumulation of pollutants in the atmosphere and their effects on human health and ecosystems persist over extended periods. Projections of urban population growth by 2060 underline the long-term challenges posed by air pollution (IQAir, 2023). Moreover, discussions on climate change and its interaction with air pollution further emphasize the need for sustained efforts to address this issue (OECD, 2020; Progiou et al., 2023).

2.4.3. What is the level of impact of this problem

Air pollution poses a high-impact problem with severe consequences for human health, the environment, and the economy. Reports explicitly link air pollution to cardiorespiratory diseases, cancer, and significant economic burdens through increased healthcare expenditure and reduced productivity (NCESD, 2018). Studies on biomass burning in Crete and PM10 exceedances in Thessaloniki further highlight its detrimental health effects and substantial impact on urban populations (Anastasaki et al., 2021; Progiou et al., 2023).

2.4.4. What is the number of people or organizations that this problem affects

Air pollution affects a vast number of people and organizations across Greece. The entire population is exposed to varying degrees of air pollution, with sectors such as healthcare, industry, transportation, and government deeply involved in managing its consequences (Fameli, 2014; NCESD, 2019). Public health impacts and the engagement of ministries and organizations underscore the widespread nature of this issue (Hellenic Statistical Authority, 2021).

2.4.5. How reversible is this problem

While some aspects of air pollution can be reversed through effective mitigation strategies, certain long-term impacts might persist. Emission reductions can significantly improve air quality over time, as suggested by mitigation strategies in various reports (Progiou et al., 2023; UNECE, 2018). However, accumulated pollutants and their effects on ecosystems and human health may not be entirely reversible due to the complexities of atmospheric processes and long-term health consequences (NCESD, 2018).

Conclusion

The scale of air pollution in Greece underscores its far-reaching and long-lasting impact. Spanning local, regional, and national levels, the problem affects diverse geographic areas, with urban centers experiencing acute challenges alongside broader national concerns. Its long-term persistence exacerbates its effects, posing significant risks to human health, ecosystems, and economic stability.

Air pollution's high impact is evident in its widespread influence on millions of individuals and numerous organizations, spanning sectors such as healthcare, industry, transportation, and governance. While some aspects of air pollution are reversible through effective mitigation strategies, others, particularly those related to long-term health and ecological damage, remain partly irreversible.

3. Strategies

Addressing wicked problems requires a structured approach that connects real-world strategies to established frameworks for problem-solving. The wicked problems matrix provides a set of strategies—breaking the problem down, identifying stakeholders, fostering collaboration, prototyping solutions, adopting adaptive management, and ensuring transparency—that can be used to tackle complex and interconnected challenges.

This section aims to identify strategies discussed in the source data and map them to the wicked problems matrix framework. By analyzing and aligning real-world approaches to these structured strategies, the section provides insights into how existing actions can be enhanced to better address the multifaceted nature of air pollution in Greece. This mapping process helps to evaluate the effectiveness of current measures and identify gaps that need to be addressed for comprehensive and sustainable problem-solving.

3.1. Breaking down the problem

This approach aligns with "Breaking the problem down" by dissecting air pollution into smaller, more manageable components, allowing for a targeted understanding of the problem's scale, sources, and impacts.

- **Source identification and quantification:** Many sources emphasize breaking down the air pollution problem by identifying and quantifying emissions from various sectors. For example, studies highlight residential heating as a major contributor to PM10 emissions in Thessaloniki (Progiou et al., 2023). Similarly, power generation, industry, vehicle emissions, and open burning are identified as primary PM2.5 sources (IQAir, 2023).
- **Pollutant-specific analysis:** The analysis focuses on specific pollutants and their impacts. Reports on transboundary air pollution examine how various pollutants affect ecosystems and human health (UNECE, 2018).
- **Regional and temporal variations:** The variability of air pollution across regions and seasons is acknowledged. For instance, differing PM2.5 levels in Greek cities highlight regional disparities, and seasonal variations are addressed in studies on Thessaloniki and rural Crete (IQAir, 2023; Anastasaki et al., 2021).

3.2. Identifying stakeholders

This approach partially aligns with "Identify stakeholders." Although stakeholders are acknowledged, the sources lack depth in analyzing their diverse interests, potential conflicts, and effective engagement mechanisms.

- **General acknowledgement:** The role of stakeholders in air quality management is often acknowledged but lacks a detailed analysis of their specific interests and perspectives (Fraport Greece, 2020; NCESD, 2018).
- **Limited stakeholder engagement:** While the importance of stakeholder awareness and support is recognized, concrete mechanisms for engaging stakeholders in decision-making processes are missing (Progiou et al., 2023).

3.3. Collaboration

This approach partially aligns with "Collaborate." Although intergovernmental and international cooperation are emphasized, examples of robust cross-sectoral collaboration are limited.

- **Intergovernmental and international cooperation:** Collaboration across governance levels is emphasized. Reports highlight the role of the EU in leading air quality improvement initiatives and the necessity of international cooperation for addressing transboundary pollution (UNECE, 2018).
- **Limited cross-sectoral collaboration:** While regulatory actions are a focus, there is a lack of examples of collaboration between sectors like industry, transportation, and research institutions to develop and implement innovative solutions (NCESD, 2019).

3.4. Prototype solutions

This approach partially aligns with "Prototype solutions." Although mitigation measures are proposed, pilot testing and iterative improvements are not emphasized.

- **Proposed mitigation measures:** Various documents propose and evaluate mitigation measures to address specific air pollution sources, such as low-emission heating systems and sustainable alternative fuels (Progiou et al., 2023; UNECE, 2018).
- **Limited pilot projects:** There is a lack of pilot projects or small-scale implementations to test and refine solutions before broader adoption (Fraport Greece, 2020).

3.5. Adaptive management

This approach partially aligns with "Adaptive management." While monitoring and evaluation are included, the lack of a flexible framework limits adaptive capabilities.

- **Monitoring and evaluation:** Monitoring air quality and evaluating implemented measures' effectiveness are highlighted as critical (Fraport Greece, 2020).
- **Limited flexibility:** Despite stressing monitoring and evaluation, there is no clear framework for adapting strategies dynamically in response to new information or changing conditions (NCESD, 2019).

3.6. Transparency

This approach partially aligns with "Be transparent." While information is accessible, mechanisms for engaging the public and fostering transparent decision-making processes are limited

- **Publicly available reports:** Reports and documents are publicly accessible, indicating transparency in sharing information about air pollution and mitigation strategies (IQAir, 2023).
- **Limited public engagement:** The sources lack mechanisms for robust public engagement, such as actively seeking feedback and addressing concerns transparently (Progiou et al., 2023).

Conclusion

The analysis of strategies for addressing air pollution in Greece highlights the value of mapping real-world approaches to the structured framework provided by the wicked problems matrix. By examining strategies such as breaking the problem down, identifying stakeholders, fostering collaboration, prototyping solutions, adopting adaptive management, and ensuring transparency, this section identifies both strengths and gaps in current practices.

Key strengths include efforts to break the problem into manageable components, such as identifying emission sources and analyzing pollutant-specific impacts, as well as ongoing intergovernmental and international collaborations. However, gaps remain in stakeholder engagement, cross-sectoral collaboration, pilot testing of solutions, and adaptive management frameworks. Additionally, while transparency is achieved through publicly available reports, there is limited public engagement in the decision-making process.

4. Proposed strategies and activities

Drawing from the analysis above and the strategies outlined in the wicked problems framework, the following strategies and activities are proposed to enhance air pollution mitigation efforts in Greece:

4.1. Enhanced stakeholder engagement

- **Conduct a comprehensive stakeholder analysis:** Identify key stakeholder groups (e.g., residents, businesses, environmental NGOs, government agencies) and map their interests, concerns, and influence related to air pollution.
- **Establish platforms for dialogue and participation:** Create mechanisms for meaningful stakeholder engagement, such as public forums, advisory committees, and online consultation platforms. These platforms will allow for gathering diverse perspectives, addressing concerns, and building consensus on mitigation strategies.

4.2. Fostering cross-sectoral collaboration

- **Establish partnerships between industry, research institutions, and government:** Facilitate collaboration to develop and implement innovative technologies for reducing emissions. For example, partnerships could focus on cleaner production processes for industries or promoting the adoption of renewable energy sources.
- **Encourage public-private partnerships:** Leverage private sector expertise and resources to support air quality improvement initiatives. This includes incentivizing businesses to adopt cleaner technologies and investing in public awareness campaigns.

4.3. Pilot projects and adaptive management

- **Implement pilot projects for proposed solutions:** Test the feasibility and effectiveness of mitigation measures on a smaller scale before widespread implementation. For instance, pilot programs could focus on promoting electric vehicles in specific regions or introducing clean heating solutions in select communities.
- **Develop an adaptive management framework:** Establish a system for continuously monitoring air quality, evaluating the impacts of implemented measures, and adapting strategies based on new information or changing circumstances. This approach involves setting clear targets, tracking progress, and making adjustments as needed to respond to emerging challenges.

4.4. Strengthening transparency and communication

- **Develop clear and accessible communication strategies:** Tailor information about air quality, health impacts, and mitigation efforts to diverse audiences. Use various communication channels (e.g., websites, social media, public service announcements) to maximize reach and engagement.

- **Make data and decision-making processes transparent:** Publicly share air quality data, methodologies for evaluating mitigation measures, and the rationale behind policy decisions. This transparency will help build trust and ensure accountability in air pollution management.

Conclusion

By incorporating these strategies and activities, Greece can adopt a more holistic, collaborative, and adaptive approach to tackling air pollution. Addressing this wicked problem requires acknowledging its complexity, engaging diverse stakeholders, and implementing solutions that are flexible, data-driven, and responsive to the evolving nature of the challenge.

5. Conclusion

This report provides a comprehensive analysis of air pollution in Greece through the lens of the Wicked Problem Matrix, shedding light on the multifaceted challenges of addressing this pressing environmental issue. The dimensions of complexity, uncertainty, conflict, and scale reveal the intricate web of variables, interdependencies, and societal impacts that define air pollution as a wicked problem. By evaluating these dimensions, the report underscores the need for multidimensional and adaptive approaches to mitigation.

Key findings include the highly complex and non-linear nature of air pollution, driven by diverse emission sources, meteorological factors, and socioeconomic dynamics. Uncertainty in predicting pollution patterns, rapid fluctuations in pollution levels, and ambiguous data further complicate effective intervention. The analysis of stakeholder conflicts highlights misaligned interests and imbalances in power, communication, and trust, underscoring the need for inclusive and transparent engagement strategies. Finally, the assessment of scale emphasizes air pollution's long-term, high-impact consequences that affect millions of people and organizations across Greece.

To address these challenges, the report maps existing mitigation efforts to the Wicked Problem Matrix strategies and identifies gaps in current practices. While progress has been made in breaking down the problem and fostering intergovernmental collaboration, significant deficiencies remain in stakeholder engagement, cross-sectoral cooperation, pilot testing, adaptive management, and public transparency.

Building on these insights, the report proposes actionable strategies and activities, including enhanced stakeholder engagement, cross-sectoral collaboration, pilot testing of solutions, and

the development of adaptive management frameworks. Strengthening transparency and communication will also be essential for fostering trust and accountability.

In conclusion, addressing air pollution in Greece demands a holistic, flexible, and collaborative approach. By aligning real-world efforts with structured problem-solving frameworks, stakeholders can better navigate the complexity of this wicked problem, fostering sustainable solutions that balance environmental, social, and economic priorities.

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Co-funded by the European Union

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EXPERIMENTATION REPORT

Mapping North Macedonia's Air Pollution on Wicked Problem Matrix

1. Introduction

Air pollution represents a significant environmental challenge in Greece, characterized by its complexity and widespread impacts on human health, ecosystems, and economic activities. This report seeks to analyze the intricate nature of air pollution within the framework of the Wicked Problem Matrix. By evaluating the variables influencing air pollution, their interdependencies, and the non-linear cause-and-effect relationships, this report provides a comprehensive understanding of the issue's multidimensionality.

Drawing on data from a range of sources, the analysis addresses key factors such as emissions from various sectors, meteorological conditions, socioeconomic drivers, and the effectiveness of policy measures. Furthermore, it highlights the regional and national scale of the problem, emphasizing the long-term implications and the need for collaborative, adaptive, and transparent approaches to mitigation.

2. Dimensions of wicked problems

2.1. Complexity

Air pollution in North Macedonia, particularly in urban areas like Skopje, poses a significant threat to public health and the environment. This report delves into the complexity of this issue, examining the multifaceted factors contributing to its persistence and the challenges in finding effective solutions. By analyzing the number of variables, their interdependencies, the level of understanding surrounding the problem, the linearity of cause-and-effect relationships, and the ambiguity involved, this report aims to provide a comprehensive overview of the complicated nature of air pollution in North Macedonia.

2.1.1. Number of variables influencing the problem

High. The sources highlight numerous variables contributing to air pollution in North Macedonia. These include:

- **Emission sources:** Energy production (particularly from lignite-fired power plants) (Republic of North Macedonia, 2020a, 2020b), industrial processes (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020), transportation (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020), domestic heating (especially wood burning) (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016), waste management (including open burning at dumpsites) (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; Republic of North Macedonia, 2020a), construction (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016), and agriculture (World Bank, 2019).
- **Geographic and meteorological factors:** Skopje's location in a valley, with specific wind patterns and temperature inversions, exacerbates pollutant buildup (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016). Climate change further influences weather conditions and pollution levels (City of Skopje & United Nations Development Programme [UNDP], 2020).
- **Socio-economic factors:** Population growth and urbanization increase energy demand (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016). Poverty may limit access to cleaner heating options (City of Skopje & UNDP, 2020). Public awareness and behavioral patterns contribute to the problem (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020a; Republic of North Macedonia, 2020).
- **Governance and institutional factors:** Inadequate coordination and communication among institutions hinder effective air quality management (City of Skopje & UNDP, 2020). Data availability and monitoring systems require improvement (World Bank, 2019; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016). Enforcement of regulations and sanctions for polluters need strengthening (World Bank, 2019).
- **Transboundary pollution:** Emissions from neighboring countries also impact air quality in North Macedonia (Klein, Gauss, Nyíri, & Steensen, 2011).

2.1.2. Interdependencies between variables

High. The analysis demonstrate strong interdependencies among the variables:

- **Emission sources and geography:** Skopje's topography and meteorological conditions interact with emissions, leading to severe pollution episodes (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016).
- **Socio-economic factors and energy use:** Urbanization drives energy demand, influencing choices between cleaner and polluting fuels (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; Republic of North Macedonia, 2020b).
- **Governance and emission control:** Effective enforcement of regulations and adoption of mitigation measures directly impact emissions from various sectors (World Bank, 2019; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016).
- **Climate change and air pollution:** Climate change alters weather patterns, potentially exacerbating air pollution and its health impacts (City of Skopje & UNDP, 2020).
- **Data availability and policymaking:** Accurate data on emissions, air quality, and source contributions are essential for developing targeted policies and measures (World Bank, 2019; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016).

2.1.3. Level of understanding the problem

Medium. The sources indicate a moderate level of understanding of the air pollution problem in North Macedonia:

- **Concrete understanding:** There is a clear recognition of the major pollutants (PM, NO2, benzene, etc.) (World Bank, 2019; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016) and their health impacts (City of Skopje & UNDP, 2020; Republic of North Macedonia, 2020). Monitoring data provide tangible evidence of pollution levels (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; World Bank, 2019). Source apportionment studies identify key contributors to PM pollution, like biomass burning (Klein et al., 2011).
- **Conceptual understanding:** The interplay between emissions, geography, meteorology, and socio-economic factors is acknowledged (Republic of North Macedonia, 2020a; Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020b). The complexity of managing air quality in a dynamic urban environment is recognized (Republic of North Macedonia, 2020b).

- **Limited theoretical understanding:** Further research is needed to fully grasp the long-term impacts of climate change on air quality, the effectiveness of specific policy interventions, and the complex interactions within the system.

2.1.4. Linearity of cause-and-effect relationship

Medium to high. The cause-and-effect relationships in air pollution are generally non-linear and complex:

- **Non-linear impacts:** Emissions from various sources interact with meteorological conditions and geographical features, leading to unpredictable pollution episodes (World Bank, 2019; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016). The formation of secondary pollutants, like PM, involves complex atmospheric reactions (Republic of North Macedonia, 2020a).
- **Feedback loops:** Climate change, influenced by emissions, can further alter weather patterns and impact air quality (City of Skopje & UNDP, 2020).
- **Policy interventions:** The effectiveness of measures depends on various factors, including enforcement, public acceptance, and technological advancements (Republic of North Macedonia, 2020b).

2.1.5. Ambiguity and difficulty in understanding

Medium. While there is a good understanding of the basic problem, ambiguities remain:

- **Data gaps:** Limited data availability for certain pollutants and time periods hinders comprehensive analysis (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016). Uncertainties in emission inventories and source apportionment studies exist (Klein et al., 2011; World Bank, 2019).
- **Complex interactions:** Fully comprehending the interplay of all contributing factors and predicting the long-term impacts of interventions remains challenging (Republic of North Macedonia, 2020b).
- **Evolving context:** Climate change, urbanization, and technological advancements continuously introduce new variables and uncertainties.

The analysis reveals that air pollution in North Macedonia is a highly complex problem, driven by a large number of interconnected variables and exhibiting non-linear cause-and-effect

relationships. While a moderate level of understanding exists regarding the major pollutants and their sources, further research is crucial to fully grasp the long-term impacts of interventions and the influence of factors like climate change. Ambiguity arises from data gaps and the constantly evolving context, requiring adaptive management strategies. Addressing this challenge demands a multifaceted approach encompassing improved data collection, strengthened institutional coordination, and the implementation of effective, context-specific mitigation measures. Public awareness and engagement are also vital for fostering behavioral changes and supporting sustainable solutions.

2.2. Uncertainty

Building upon the complexity analysis of air pollution in North Macedonia, this report delves further into the uncertainties associated with this wicked problem. The analysis focuses on the predictability of the problem, its rate of change, the ambiguity surrounding its understanding, and the potential risks associated with negative outcomes.

2.2.1. Predictability of the problem

Medium to high. While the sources provide a basis for understanding general trends and contributing factors to air pollution, predicting specific pollution episodes and long-term outcomes remains challenging.

- **Meteorological variability:** Weather patterns, particularly wind speed and direction, temperature inversions, and precipitation, significantly influence pollution levels and are inherently unpredictable (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020).
- **Emission fluctuations:** Emissions from various sectors, such as transportation, domestic heating, and industrial activities, fluctuate based on factors like energy demand, economic activity, and behavioral patterns (Srbinovska et al., 2023; Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020; Srbinovska et al., 2023).
- **Implementation uncertainties:** The effectiveness of mitigation measures, even when planned, depends on their successful implementation, enforcement of regulations, and public acceptance, introducing uncertainties in predicting outcomes (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; City of Skopje & UNDP, 2020).

2.2.2. Rate of change of the problem

Medium to high. Air pollution in North Macedonia is a dynamic problem influenced by several factors that contribute to its rapid evolution:

- **Urbanization and population growth:** Rapid urbanization and population growth in Skopje and other cities escalate energy demand and traffic congestion, impacting emission levels (Srbinovska et al., 2023; City of Skopje & UNDP, 2020).
- **Climate change:** Climate change introduces additional uncertainties by altering weather patterns, potentially exacerbating the frequency and intensity of pollution episodes and influencing long-term trends (Srbinovska et al., 2023; City of Skopje & UNDP, 2020).
- **Technological advancements:** The adoption of new technologies, both in emission sources and pollution control, can have unpredictable impacts on air quality (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020).

2.2.3. Ambiguity and difficulty in understanding

Medium. As previously discussed, the understanding of air pollution in North Macedonia is at a moderate level, with existing ambiguities further contributing to uncertainty:

- **Data gaps:** Limited data availability for specific pollutants, like PM2.5 and heavy metals, as well as for certain time periods, restricts comprehensive analysis and prediction (Srbinovska et al., 2023; Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020).
- **Model limitations:** While models provide insights into pollution dispersion and the impact of measures, they rely on assumptions and simplifications, leading to uncertainties in their predictions (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; City of Skopje & UNDP, 2020).
- **Conflicting information:** The sources occasionally present differing perspectives on the severity of the problem or the effectiveness of certain measures, adding to the ambiguity.

2.2.4. Level of risk for negative outcomes

High. The sources consistently highlight significant risks associated with air pollution in North Macedonia:

- **Public health impacts:** Air pollution poses severe health risks, particularly for vulnerable populations. It contributes to respiratory and cardiovascular diseases,

premature mortality, and other health issues, with potentially substantial economic and social costs (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020; World Bank, 2019).
- **Environmental degradation:** Air pollution negatively impacts ecosystems, biodiversity, and water quality, with potential long-term consequences (City of Skopje & UNDP, 2020).
- **Economic costs:** Health impacts associated with air pollution lead to increased healthcare expenses, reduced productivity, and lost workdays, imposing a burden on the economy (World Bank, 2019).

Conclusion

The uncertainty surrounding air pollution in North Macedonia adds another layer of complexity to this wicked problem. The limited predictability, the dynamic nature of the problem, the presence of ambiguities, and the high risk of severe negative outcomes necessitate a proactive and adaptive approach to management. Addressing the uncertainties head-on through robust risk assessments and preparedness strategies can help mitigate the potential for adverse consequences and build a more resilient future for North Macedonia.

2.3. Conflict

This report examines the conflict dimensions of air pollution in North Macedonia, focusing on the number of stakeholders involved, the alignment of their interests and values, the balance of power among them, their communication patterns, and the level of trust they share. The analysis draws upon the provided sources, recognizing their limitations in comprehensively addressing stakeholder perspectives.

2.3.1. Number of stakeholders

High. Air pollution in North Macedonia affects a large number of stakeholders, including:

- **Government institutions:** Multiple ministries and agencies are responsible for different aspects of air quality management, including the Ministry of Environment and Physical Planning (MoEPP), Ministry of Economy, Ministry of Health, and municipal governments (World Bank, 2019; United Nations Country Team, 2023; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016). The sources indicate that coordination and cooperation between these institutions are crucial for effective air quality management (World

Bank, 2019; GFA Consulting Group GmbH, GFA South East Europe LLC, & Ramboll Group A/S, 2020).

- **Industry and businesses:** Various sectors, such as energy production, manufacturing, transportation, and construction, contribute to air pollution and are impacted by regulations and mitigation measures (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; United Nations Country Team, 2023). The sources highlight the need to engage with industries to promote cleaner practices and technologies (World Bank, 2019; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016).
- **Civil society organizations:** Environmental NGOs and community groups advocate for improved air quality and represent citizen concerns (United Nations Country Team, 2023; GFA Consulting Group GmbH, GFA South East Europe LLC, & Ramboll Group A/S, 2020). The sources recognize the role of civil society in policy-making and implementation (United Nations Country Team, 2023; GFA Consulting Group GmbH, GFA South East Europe LLC, & Ramboll Group A/S, 2020).
- **Citizens:** The entire population is affected by air pollution, with varying degrees of vulnerability based on location, health status, and socioeconomic factors (World Bank, 2019; City of Skopje & United Nations Development Programme [UNDP], 2020). The sources emphasize the importance of public awareness and citizen engagement in addressing air pollution (World Bank, 2019; City of Skopje & UNDP, 2020).

2.3.2. Alignment of interests and values

Partially aligned to misaligned. While all stakeholders share a common interest in clean air and a healthy environment, their specific priorities and approaches to the problem can differ, leading to conflict:

- **Economic growth vs. environmental protection:** The need for economic development, particularly in energy and industry sectors, often clashes with environmental regulations and the push for cleaner technologies (GFA Consulting Group GmbH, GFA South East Europe LLC, & Ramboll Group A/S, 2020; Republic of North Macedonia, 2020). This tension is evident in the sources, which highlight the challenges of balancing economic growth with environmental sustainability (GFA Consulting Group GmbH, GFA South East Europe LLC, & Ramboll Group A/S, 2020; Republic of North Macedonia, 2020).
- **Short-term costs vs. long-term benefits:** Implementing effective mitigation measures often requires significant upfront investments and potential economic burdens, which can conflict with the pursuit of short-term economic gains (United Nations Country

Team, 2023). The sources acknowledge the need for financial resources and investment in environmental projects (United Nations Country Team, 2023; World Bank, 2019).

- **Individual Behavior vs. Collective Action:** Encouraging behavioral changes, such as reducing car usage or switching to cleaner heating sources, can be challenging and may face resistance from individuals prioritizing personal convenience or economic constraints (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; Barandovski, Stafilov, Šajn, Frontasyeva, & Bačeva, 2013). The sources underscore the importance of information campaigns and incentives to promote behavioral change (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; World Bank, 2019).

2.3.3. Power balance

Imbalanced. The power dynamics among stakeholders in addressing air pollution are unevenly distributed:

- **Government influence:** Government institutions hold significant power in setting regulations, enforcing standards, and implementing policies (World Bank, 2019; City of Skopje & UNDP, 2020). However, their effectiveness depends on political will, capacity, and resources (United Nations Country Team, 2023). The sources point to limitations in government capacity and enforcement mechanisms (United Nations Country Team, 2023; World Bank, 2019).
- **Industry lobbying:** Industries and businesses often exert considerable influence through lobbying efforts, potentially impacting the stringency of regulations or delaying the adoption of cleaner practices (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016). The sources highlight the need for stronger regulations and enforcement to address industrial pollution (Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; Republic of Macedonia, 2017).
- **Citizen participation:** While citizens are ultimately the most affected, their power to influence decisions often depends on their ability to organize, advocate for their interests, and hold decision-makers accountable (City of Skopje & UNDP, 2020). The sources call for enhanced citizen participation and empowerment in decision-making processes (City of Skopje & UNDP, 2020; United Nations Country Team, 2023).

2.3.4. Communication

Average to poor. The sources point to limitations in communication among stakeholders:

- **Information gaps:** The availability and accessibility of data and information on air quality, emission sources, and the impacts of pollution vary among stakeholders, hindering informed decision-making (Macedonian Environmental Information Center, 2020; GFA Consulting Group GmbH, GFA South East Europe LLC, & Ramboll Group A/S, 2020).
- **Limited public engagement:** Opportunities for meaningful public participation in developing and implementing air quality plans appear limited, potentially leading to a lack of ownership and support for solutions (City of Skopje & UNDP, 2020).
- **Transparency challenges:** Transparency in decision-making processes, particularly regarding industrial emissions and regulatory enforcement, can be lacking, contributing to mistrust and hindering collaboration (City of Skopje & UNDP, 2020; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016).

2.3.5. Level of trust

Medium to low. The sources suggest that trust among stakeholders in addressing air pollution is often limited:

- **Government accountability:** Public trust in government institutions to effectively address environmental issues can be low due to perceptions of corruption, lack of transparency, or inadequate enforcement of regulations (City of Skopje & UNDP, 2020).
- **Industry credibility:** The credibility of industries and businesses in prioritizing environmental protection and complying with regulations can be questioned, particularly in cases of non-compliance or perceived prioritization of profit over public health (Macedonian Environmental Information Center, 2020).
- **Conflicting information:** The presence of conflicting information from different sources, particularly regarding the severity of the problem or the effectiveness of certain measures, can erode trust among stakeholders (World Bank, 2019; United Nations Country Team, 2023).

Conclusion

The conflict dimensions of air pollution in North Macedonia highlight the need for improved governance, enhanced communication, and trust-building measures to foster collaboration among stakeholders. Addressing the power imbalances and ensuring meaningful participation of citizens and civil society organizations are crucial for developing equitable and sustainable solutions (City of Skopje & UNDP, 2020; United Nations Country Team, 2023). Transparent

and accountable decision-making processes, along with effective enforcement of regulations, can help restore trust and ensure the effective implementation of measures to improve air quality (City of Skopje & UNDP, 2020). However, it is important to note that the sources provided primarily focus on technical and policy aspects of air pollution management and do not delve deeply into the interests, values, and perspectives of various stakeholders.

2.4. Scale

Air pollution in North Macedonia is a critical environmental and public health issue that affects a significant portion of the population, particularly in urban centers. The problem is compounded by a range of contributing factors, including industrial emissions, traffic congestion, domestic heating, and geographic conditions. This section examines the scale and impact of air pollution in the country, considering its spatial and temporal reach, level of impact, and the number of individuals and organizations affected. Furthermore, it explores the potential for reversing the effects of air pollution, highlighting the importance of effective policies and long-term sustainable solutions.

2.4.1. Spatial impact

National. Air pollution is a significant problem in cities and urban centers across North Macedonia (World Bank, 2019). The sources highlight pollution hot spots in all areas of the country, with even the population-weighted mean exposure to PM2.5 exceeding the WHO guideline value (World Bank, 2019).

Studies and reports indicate air pollution concerns in various locations, including Skopje (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016), Veles (Barandovski, Stafilov, Šajn, Frontasyeva, & Bačeva, 2013), Tetovo (Barandovski et al., 2013), Radoviš (Barandovski et al., 2013), and Kavadarci (Barandovski et al., 2013).

2.4.2. Temporal impact

Long-term. Air pollution has been a persistent problem in North Macedonia for many years (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020). The sources indicate that addressing this issue requires long-term planning and sustainable solutions, including investments in infrastructure, technology, and behavioral change.

Climate change projections suggest a potential exacerbation of air pollution in the future, particularly during the winter months (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020; City of Skopje & United Nations Development Programme [UNDP], 2020).

2.4.3. Level of impact

High. Air pollution poses a significant threat to public health, leading to premature deaths, respiratory illnesses, and other health problems (World Bank, 2019; Barandovski et al., 2013; City of Skopje & UNDP, 2020). The economic costs associated with air pollution, including healthcare expenses and productivity losses, are substantial. Air pollution also negatively impacts the environment, contributing to climate change and ecosystem degradation.

2.4.4. Number of people and organizations affected

High. Air pollution affects the entire population of North Macedonia, with certain groups, such as children, the elderly, and those with pre-existing health conditions, being particularly vulnerable (World Bank, 2019; City of Skopje & UNDP, 2020). Multiple government institutions, industries, businesses, and civil society organizations are involved in managing and mitigating air pollution.

2.4.5. Reversibility

Partly reversible. While some aspects of air pollution can be mitigated through effective policies, technological advancements, and behavioral changes, certain long-term impacts, such as health consequences or climate change contributions, may be irreversible. The sources emphasize the urgency of action to prevent further deterioration of air quality and minimize the long-term consequences of this problem (World Bank, 2019).

Conclusion

Air pollution in North Macedonia is a complex and persistent problem that poses serious health, environmental, and economic risks. The broad spatial and temporal impacts demonstrate the urgency for coordinated actions across various sectors and levels of government. Although some aspects of air pollution can be mitigated, the long-term consequences, such as adverse health outcomes and environmental degradation, may be irreversible without immediate and sustained efforts.

3. Strategies

Air pollution in North Macedonia remains a persistent and complex challenge that affects both public health and the environment. The country has implemented a variety of strategies and actions to address this issue, with a focus on key sectors such as domestic heating, transportation, industry, and waste management. These efforts, while significant, need to be continuously refined and expanded to meet both current and future air quality goals. This section reviews the existing strategies and actions taken by North Macedonia to combat air pollution, examining their effectiveness and areas for improvement. Additionally, it proposes new strategies and activities that could enhance the country's approach to solving the air pollution problem, promoting long-term sustainability and improved public health outcomes. Through a comprehensive approach involving stakeholders, innovation, and adaptive management, North Macedonia can continue to make progress in improving air quality and mitigating the adverse effects of pollution.

3.1. Analysis of existing strategies and actions

3.1.1. Break the problem down

Sectoral approach: North Macedonia utilizes a sectoral approach, targeting major polluting sectors such as:

- **Domestic heating:** Programs promoting cleaner heating systems, subsidies for pellet stoves and inverters, and regulations on wood burning (United Nations Country Team, 2023; Ministry of Environment and Physical Planning, Republic of North Macedonia, 2022).
- **Transportation:** Promoting public transportation, vehicle scrappage programs, fuel quality improvements, and stricter emission standards for vehicles (World Bank, 2019; Ministry of Environment and Physical Planning, Republic of North Macedonia, 2022; Risteska, Sulejmani, & Veljanov, 2016).
- **Industry:** Enforcement of emission limits, promotion of cleaner technologies, and financial incentives for pollution control measures (World Bank, 2019; Ministry of Environment and Physical Planning, Republic of North Macedonia, 2022; Risteska et al., 2016; Ministry of Environment and Physical Planning, Republic of Macedonia, 2017).
- **Waste Management:** Improving waste collection and treatment, promoting recycling, and reducing landfill emissions (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020; Risteska et al., 2016).

- **Geographic Focus:** Air Quality Improvement Plans specifically target heavily polluted areas like Skopje and Tetovo (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2022; Ministry of Environment and Physical Planning, Republic of North Macedonia & Finnish Meteorological Institute, 2016; Risteska et al., 2016).

3.1.2. Identify stakeholders

- **Intersectoral Groups:** Formation of groups with representatives from various government ministries, industries, and civil society to address air quality (Risteska et al., 2016).
- **Public Consultations:** Engaging citizens and communities in the development of air quality plans (City of Skopje & UNDP, 2020).

3.1.3. Collaborate

International cooperation: Collaboration with international organizations like the EU and UNDP on air pollution projects and funding (United Nations Country Team, 2023; Ministry of Environment and Physical Planning, Republic of North Macedonia, 2022; Risteska et al., 2016).

3.1.4. Prototype solutions:

- **Pilot projects:** Implementation of pilot projects, such as the Bitola Air Quality Improvement Plan, to test the effectiveness of different measures (Risteska et al., 2016).
- **Subsidy programs:** Introduction of subsidy programs for cleaner heating systems and energy efficiency to assess their impact on emissions (United Nations Country Team, 2023; Ministry of Environment and Physical Planning, Republic of North Macedonia, 2022).

3.1.5. Adaptive anagement:

Regular review and revision of air quality plans based on monitoring data, emission trends, and implementation experiences (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2020; Risteska et al., 2016).

3.1.6. Be transparent

- **Data publication:** Publicly available air quality data from monitoring stations and emission inventories (Risteska et al., 2016).
- **Reporting:** Regular reporting on the progress of air quality improvement efforts to national and international bodies (Ministry of Environment and Physical Planning, Republic of North Macedonia, 2022).

3.2. Proposed strategies and activities:

Building upon existing efforts, the following strategies and activities can contribute to solving the wicked problem of air pollution in North Macedonia:

3.2.1. Enhance stakeholder engagement:

- Establish a permanent multi-stakeholder platform for air quality management with clear roles, responsibilities, and decision-making mechanisms.
- Conduct regular and inclusive public consultations at all stages of policy development and implementation.
- Facilitate dialogue between industries and communities to address concerns and build consensus on solutions.

3.2.2. Strengthen regulatory framework and enforcement:

- Develop and enforce stricter emission standards for all polluting sectors, aligning with EU regulations.
- Implement a robust monitoring and enforcement system with clear penalties for non-compliance.
- Increase transparency in regulatory processes and ensure public access to information on emissions and compliance.

3.2.3. Promote sustainable and affordable solutions:

- Expand financial incentives and support programs for households and businesses to adopt cleaner technologies, including energy efficiency measures and renewable energy sources.
- Invest in public transportation infrastructure and services to provide affordable and reliable alternatives to private vehicles.
- Support research and development of innovative air pollution control technologies and sustainable practices.

3.2.4. Empower local communities:

- Provide capacity building and resources to local governments and communities to develop and implement tailored air quality improvement plans.
- Support community-based initiatives to promote awareness, behavior change, and local solutions to air pollution.

3.2.5. Foster a culture of environmental responsibility:

- Integrate air quality considerations into all relevant policies and planning processes, including urban planning, transportation, and economic development.
- Launch comprehensive public awareness campaigns to educate citizens about the impacts of air pollution and promote individual and collective actions to improve air quality.

By implementing these strategies and activities, North Macedonia can effectively address the multi-faceted challenge of air pollution, promoting both environmental sustainability and public health. It is crucial to acknowledge that these solutions require long-term commitment, sustained investment, and ongoing collaboration among all stakeholders.

4. Conclusion

Air pollution in North Macedonia is a persistent and multifaceted challenge that requires a coordinated and adaptive approach to achieve meaningful improvements. This report has illustrated the complexity, uncertainty, conflicts, and scale associated with air pollution, highlighting the interplay of numerous variables, stakeholder dynamics, and the broad-reaching consequences of inaction. While progress has been made through existing strategies targeting key sectors such as domestic heating, transportation, and industry, significant gaps remain in regulatory enforcement, stakeholder engagement, and the integration of sustainable practices.

Moving forward, addressing air pollution will require enhanced collaboration among government institutions, industries, civil society, and citizens. Strengthened regulatory frameworks, innovative solutions, and public engagement are essential to mitigate the health, environmental, and economic impacts of air pollution. Furthermore, fostering a culture of environmental responsibility and integrating air quality considerations into broader planning processes can ensure long-term sustainability.

This report underscores the importance of sustained investment, capacity building, and inclusive policy-making to confront the wicked problem of air pollution in North Macedonia. By implementing a comprehensive, transparent, and adaptive strategy, the country can move toward a cleaner, healthier, and more sustainable future.

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